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ENGINEERING DESIGN HANDBOOK

METRIC CONVERSION GUIDE

HQ, US ARMY MATERIEL DEVELOPMENT AND READINESS COMMAND JULY 1976

DEPARTMENT OF THE ARMY
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TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

CHAPTER 7
EXAMPLES

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1-1 GENERAL

For most scientific and technical work it generally is accepted that the International System of Units (SI) is superior to all other systems of units. The SI is the most widely accepted and used language for scientific and technical data and specifications. The National Aeronautics and Space Administration (NASA) and the Environmental Protection Agency (EPA) now require that all contractor and internal reports use SI units. In 1975, the Deputy Secretary of Defense established policies (1) of using the "international metric system" (i.e., the SI) in all activities of the Department of Defense (DOD) consistent with operational, economical, technical, and safety considerations; and (2) of considering the use of the SI in the procurement of all supplies and services and particularly in the design of new materiel. These new policies of the DOD establish clearly a trend of increasing use of the SI within the DOD and in particular in the US Army Materiel Development and Readiness Command (DARCOM), and establish the need for this handbook.

The general purpose of this handbook is to prepare DARCOM personnel — technicians and engineers — for increased use of the SI, or as it is generally referred to, the metric system. This means, specifically, giving DARCOM personnel (1) the tools required to convert the units of physical quantities and equations to SI units, (2) the information needed to interpret specifications and the results of the work of others expressed in SI units, and (3) the information needed to write specifications and document their own work in SI units. Additionally, information on the history of metrication in the United States is presented in par. 1-3.

1-2 ORGANIZATION OF HANDBOOK

The organization of this handbook is intended to facilitate use of the information presented herein by individuals in DARCOM. Each chapter addresses specific and related aspects of the International System of Units, its use, and the conversion of the units of quantities and equations. To the extent practical, each chapter is presented such that it can be read, understood, and used without studying the entire handbook or even the preceding chapters. For example, Chapter 4 can be studied for the purpose of learning how to convert the units of quantities and equations independently of the remainder of the handbook.

The following outline of the contents of the handbook, chapter-by-chapter, can be used as a guide to the user of this handbook:

1. **CHAPTER 2 THE INTERNATIONAL SYSTEM OF UNITS.** This chapter contains all information related to what constitutes the SI. This includes the definitions of SI units, brief descriptions of the development and evolution of metric units, and prefixes that are used with the SI units. Table 2-3, in particular, should be consulted when there are questions concerning what units are SI or are non-SI but may be used with SI units. Additionally, Table 2-3 contains references to pages in this handbook which contain information related to specific units and categories of units.

2. **CHAPTER 3 GUIDELINES FOR THE USE AND APPLICATION OF THE INTERNATIONAL SYSTEM OF UNITS.** This chapter is intended to assist in achieving uniformity in the use of SI units in reports and documentation (with the exception of engineering drawings which are covered in Chapter 6). Subjects covered include proper use of prefixes, the formation of derived units, numerical value format, and spelling. Table 3-7 lists preferred prefixes for specific units, exceptions to the rules for prefixes and derived units, and special non-SI units which are used in specific industries and disciplines.

3. **CHAPTER 4 CONVERSION OF UNITS.** Methods for converting the units of quantities and equations are presented in this chapter. Dimensional analysis is the basis for the conversion method; dimensional analysis is not treated rigorously but as a practical and logical tool. Basic concepts in mechanical and electromagnetic quantities are presented to facilitate the conversion of mechanical and

electromagnetic units. Significant digits and accuracy of measurement and estimates as they relate to conversion of units are covered.

4. **CHAPTER 5 CONVERSION FACTORS AND NUMERICAL FACTORS.** Unit conversion factors are listed both alphabetically and by category of physical quantity. Also presented are lists of "dimensionless" constants and physical constants in SI units.

5. **CHAPTER 6 ENGINEERING DRAWINGS.** The use of SI units in engineering drawings, including "dual dimensioning", is covered in this chapter. Methods for converting toleranced dimensions to SI are presented.

6. **CHAPTER 7 SAMPLE CALCULATIONS.** Examples of conversion to SI units of quantities, equations, graphs, and tables taken from a number of US Army Materiel Command Engineering Design Handbooks are presented.

The remainder of Chapter 1 relates a brief history of metrication in the U.S.

1-3 METRICATION IN THE UNITED STATES

The history of metrication in the U.S. is one of proposals, consideration, and, until recently, little action. This history is covered adequately and at various levels in a number of sources (Refs. 1, 2, and 3). Some of the most interesting and important events of the past 200 yr are presented in the paragraphs that follow:

1790: Thomas Jefferson proposed a decimal system of weights and measures in a report accepted by Congress. Jefferson's system was based on a unit of length, a "new foot", which was approximately equal to the "old foot" and was based upon the swing of a standard pendulum. This pendulum having a period of two seconds was also to be the time standard for the U.S. The new foot was to be divided into ten new inches and was to be the basis for deriving standard units for area, volume, weight, and force. The proposal was not adopted by Congress. (At this time, the Paris Academy of Sciences was developing a radically different system based upon scientific principles and a unit of length named the metre defined as a specific fraction of the earth's circumference. Decimal relationships were established for forming larger and smaller units of length and other quantities.)

1821: John Quincy Adams proposed to the Congress a two-phase plan which would lead to an international and uniform metric system of measurement. Adams clearly identified five advantages of the metric system: the "invariable" standard of length, the single unit for weight and single unit for volume, the decimal relationship between units, the relationship of weight units to French coinage, and the uniform and precise terminology. Congress again took no action on Adam's proposal.

1832: The Treasury Department adopted English standards to meet the needs of customs houses.

1863: A committee of the National Academy of Sciences (which had been formed by President Lincoln) was appointed at the request of the Secretary of the Treasury to reconsider weights, measures, and coinage. This committee submitted a report favorable to adoption of the metric system. The report was received with approval by Congressman John A. Kasson, chairman of the newly established House Committee on Coinage, Weights and Measures. Consequently, this same House Committee reported favorably to the Congress three metric bills which were eventually passed in 1866. These bills provided for the following:

1. Use of the metric system was legalized.
2. Use of metric scales for foreign mail was directed.
3. Distribution of metric standards to the states was directed.

1873: Considerable public interest had developed along with strong controversy among educators concerning the advantages of adopting the metric system. In 1873, the American Metrological Society was founded and did much to inform people about the metric system and to maintain interest in and consideration of the metric system.

1875: Following five years of meetings in Paris, seventeen nations including the U.S. ratified the Treaty of the Metre. This convention and treaty accomplished the following: the metric system was reformulated

and the accuracy of its standards was refined, the construction of new physical standards and distribution of copies to member nations was provided for, organization and machinery for international action on weights and measures was established, and the International Bureau of Weights and Measures was created.

1893: The Secretary of the Treasury by administrative order established the new metric standards of length and mass as the fundamental standards of the U.S. The U.S. customary units — yard, pound, etc. — were defined as fractions of the standard metric units.

The most significant events in the preceding are the Act of 1866 which legalized the metric system and the 1893 administrative order establishing metric standards as fundamental standards of the U.S. These establish a legal basis for voluntary metrication by industrial and governmental sectors of the country. They are, in fact, the legal basis for all metrication activities in the U.S. at the present.

1896: A bill making the metric system the only legal system was passed by Congress, but, in a reconsideration of the bill, it was sent back to committee and never reappeared. Following the failure of this bill, the arguments for and against metrication solidified and there was much controversy and no action. At the turn of the century the opposition was so strong that proponents of metrication gave up for a number of years.

1916: The American Metric Association was formed in New York. One year later the World Trade Club, a pro-metric organization, was established in San Francisco. In spite of these organizations and as a result of international economic and political situations, the metric question was not seriously considered until the 1950's. Then, the opening of the space age and the reemergence of European nations as industrial powers again focused attention on the need for an international system of measurement.

1960: The metric system became the common system of measurement for all 43 Treaty of the Metre signatories including the U.S.

1968: Public Law 90-472 authorizing the Department of Commerce to conduct the United States Metric Study was passed by Congress.

1975: The Deputy Secretary of Defense established the following policies for all components of the Department of Defense (Ref. 4):

1. The Department of Defense will use the international metric system in all of its activities consistent with operational, economical, technical, and safety considerations.
2. Effective immediately, the international metric system will be considered in the procurement of all supplies and services and particularly in the design of new materiel. It will be used when determined to be in the best interest of the Department of Defense.

On December 8, 1975, Metric Bill S-100 was passed by the U.S. Senate and signed into law (PL 94-168) by the President on December 23, 1975 (Ref. 5). This law declares that it is the policy of the U.S. to coordinate and plan the increasing use of the metric system in the U.S., and the law establishes a United States Metric Board (USMB) to coordinate voluntary conversion to the metric system. This board consists of seventeen members representing engineers, scientists, manufacturers, commerce, labor, the States, small business, construction, standards making organizations, educators, consumers, and other interests. Although the board has no compulsory powers, it is engaged in very important activities that can strongly influence the course of metrication in the U.S. The board develops and carries out a broad program of planning, coordination, and public education. Two of the most significant activities of the board are:

1. The preparation of a report to be submitted in one year to the Congress and the President. This report will make recommendations on the need for and implementation of a structural mechanism for converting the units used in statutes, regulations, and other laws at all levels of Government.
2. The submission of annual reports to the Congress and the President on the status of metrication and recommending legislation or executive action needed to implement programs accepted by the board.

REFERENCES

1. NBS SP 345, *A Metric America: A Decision Whose Time Has Come*, Dept. of Commerce, National Bureau of Standards, July 1971.
2. NTIS AD/A-006 038, *The Impact of Metrication on the Defense Standardization Program*, Dept. of

Commerce, National Technical Information Service, November 1974.
3. American National Standards Institute, *Measuring Systems and Standards Organizations*, ANSI, NY, n.d.
4. National Bureau of Standards, Metric Information Office, *Current Metric Activity*, July 1975.
5. Public Law 94-168, 94th Congress, H. R. 8674, December 23, 1975, 89 STAT. 1007-1012.

CHAPTER 2
THE INTERNATIONAL SYSTEM OF UNITS

The International System of Units, abbreviated SI, as defined in International Standard ISO 1000 (Ref. 2) is described in this chapter. International Standard ISO 1000 was approved by International Organization of Standards (ISO) Member Bodies from 30 countries including the United States.

The SI consists of the following:

1. *Seven base units*
2. *All the derived units*
3. *Two supplementary units*
4. *The series of approved prefixes for multiples and submultiples of units.*

These units, their definitions, their symbols, some information on their evolution to present form, and the formation of multiple and submultiple units are presented in this chapter. Information related to style, use, and format is given in Chapter 3.

2-1 THE THREE CLASSES OF UNITS IN THE SI

The units of the International System of Units are divided into three classes (Ref. 1):

1. Base units
2. Derived units
3. Supplementary units.

Scientifically and technically this classification is partially arbitrary. The 10th General Conference of Weights and Measures (1954) adopted as base units of the SI the units of the quantitites: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity which by convention are regarded as dimensionally independent (Ref. 1). Associated with these quantities are seven well-defined units. This action was taken in the interest of achieving the advantages of having a single, practical, internationally accepted system for trade, education, science, and technology.

The derived units are the units of quantities that can be formed by combining base quantities and other derived quantities according to the rules of algebra. The units of these derived quantities are such that no numerical factors (factors of proportionality) are introduced into the fundamental equations defining these quantities. Thus the SI — composed of seven base units, a growing number of derived units, and the supplementary units discussed in the paragraphs that follow and par. 2-4 — forms a coherent system of units.* Examples of derived quantities are speed, energy, and magnetic flux.

Two units were adopted by the 11th General Conference of Weights and Measures (1960) as supplementary units primarily because it was not agreed that the two units were either base units or derived units (Ref. 1). The quantities involved are plane angle and solid angle. Actually they may be regarded as base units or as derived units (Ref. 2).

2-3 BASE UNITS OF THE SI

2-3.1 SUMMARY

The SI is based on the units of seven physical quantities which by convention are considered dimensionally independent and by international agreement and acceptance are uniformly defined. The quantities, unit names, and symbols are given in Table 2-1 (Ref. 2).

* A coherent system of units is one in which all derived units can be expressed as products of ratios of the base units (and, in the SI, the supplementary units) without the introduction of numerical factors.

TABLE 2-1
BASE UNITS

Quantity	Base Unit name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

2-2.2 DEFINITIONS OF BASE UNITS

The seven base units of the SI are defined, as follows, in International Standard ISO 1000 (Ref. 2):

1. *metre.* The metre is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.

2. *kilogram.* The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

3. *second.* The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

4. *ampere.* The ampere is that constant electric current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

5. *kelvin.* The kelvin unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

6. *mole.* The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

7. *candela.* The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.

2-2.3 DISCUSSION OF BASE UNITS

The paragraphs that follow are intended to give some insight into the evolution of the base units of the SI. The General Conference of Weights and Measures (CGPM) is referred to frequently in the presentation. The CGPM is one of the bodies of the International Organization of Weights and Measures founded in Paris in 1875 by the Treaty of the Metre (Ref. 3). The CGPM coordinates, reviews, and acts in the interests of its member nations on matters related to uniformity in weights and measures. The organization recognizes only the metric system.

2-2.3.1 Unit of Length

The present definition of the metre was adopted by the General Congress of Weights and Measures in 1960 (Ref. 1). Originally the metre was chosen as one 40-millionth of the meridian through Paris (Ref. 4). The original determination of this length was used to build an international prototype of platinum-iridium (a physical standard). Because of inaccuracies in measuring one 40-millionth of the meridian, the physical standard itself became the accepted basis for the metre instead of the original definition.

Because of the desirability of being able to reproduce the length of one metre at different locations and without depending on one primary physical standard, the presently accepted definition of the metre was developed. This definition in terms of a specific number of wavelengths of light of a precise frequency and corresponding to a specific transition between two electron energy levels of the krypton-86 atom allows for

the recreation of a primary standard in some laboratories throughout the world. The original platinum-iridium prototype is still maintained at Sèvres, France, by the International Bureau of Weights and Measures.

2-2.3.2 Unit of Mass

Probably the definition of the kilogram should be written:

> The kilogram is the unit of mass [and it is *not* the unit of weight or of force]; it is equal to the mass of the international prototype of the kilogram.

Confusion about what units are force or weight and mass, and how to convert from one to the other is likely the most significant problem encountered in working with systems of units.*

The 1st CGPM in 1889 legalized the international prototype of the kilogram (Ref. 1). This platinum-iridium prototype is the world's primary standard for the kilogram and it is maintained at Sèvres under conditions specified by the CGPM in 1889. Secondary standards of platinum-iridium or stainless steel are made by direct comparison with the primary standard at Sèvres.

Of the seven base units of the SI, the kilogram is the only one not defined in terms of physical measurements that can be made in a properly equipped laboratory. It is the only base unit with a prefix; i.e., kilo-.

2-2.3.3 Unit of Time

The original definition of the unit of time, the second, was a fraction, 1/86 400, of the mean solar day (Ref. 1). Measurements of the mean solar day have demonstrated, however, that irregularities in the earth's rotation do not allow the desired accuracy. The 11th CGPM in 1960 adopted a new definition of the second based on the tropical year. This resulted in improved precision. By that time, research results demonstrated that an atomic standard based on transitions between energy levels in an atom or molecule was practical and resulted in greater precision. Thus, the 13th CGPM in 1967 adopted the present definition based on transitions between hyperfine lines of the ground state of the cesium-133 atom.

2-2.3.4 Unit of Electric Current

The present definition of the ampere was adopted by the 9th CGPM in 1948. This replaced an earlier "international" ampere which had been adopted around 1900 (Ref. 1). Note that the definition of the ampere is the same in the SI and in the customary system of units used in the U.S.

2-2.3.5 Unit of Thermodynamic Temperature

The 10th CGPM in 1954 selected the triple point of water as a fundamental fixed point and assigned to it the temperature 273.16 degree Kelvin (symbol °K) (Ref. 1). The 13th CGPM in 1967 adopted the name kelvin (symbol K) in place of the degree Kelvin and defined the unit of Thermodynamic Temperature as given in the preceding. At the same time it was decided that the unit kelvin and its symbol K should also be used to express an interval or a difference of temperature.

$$t(°\mathrm{C}) = T(\mathrm{K}) - 273.15 \tag{2-1}$$

where t is Celsius temperature and T is thermodynamic temperature.

The assigned value of 273.16 kelvin as the thermodynamic temperature at the triple point of water and equation $t = T - 273.15\mathrm{K}$ defining the Celsius temperature scale imply that at a thermodynamic temperature of 0 K the Celsius temperature is −273.15 °C and not −273.16 °C, and that at the triple point of water the Celsius temperature is 0.01 °C. This is correct!

2-2.3.6 Unit of Amount of Substance

Units of amount of substance such as "gram-atom" and "gram-molecule" have been used to specify amounts of chemical elements and compounds (Ref. 1). These units were related to atomic weight and molecular weight which are, in fact, relative masses. Atomic weight was originally referred to as the atomic

*Mass, weight, force, acceleration and their associated units are discussed at length in Chapter 4.

weight of oxygen which by general agreement was 16. Physicists generally assigned the atomic weight 16 to one of the isotopes of oxygen; chemists assigned the same atomic weight to naturally occurring oxygen — a variable mixture of isotopes 16, 17, and 18. In 1960 chemists and physicists agreed that atomic weight should be assigned to carbon 12, thus resulting in a unified scale of relative atomic mass.

The unit of amount of substance is the mole (symbol mol) and it is based on the number of atoms in 0.012 kilogram of carbon 12. The mass 0.012 kilogram was selected by international agreement.

2-2.3.7 Unit of Luminous Intensity

The units of luminous intensity prior to 1948 were based on frame or incandescent filament standards (Ref. 1). The International Commission on Illumination proposed a "new candle" as a standard for luminous intensity which was adopted by the 9th CGPM in 1948. The new candle is a black body of specific area at very precise temperature and pressure. The unit of luminous intensity thus defined was given the name candela in 1948.

2-3 SUPPLEMENTARY UNITS

At present, there are only two units, both purely geometrical, in the SI which are classified as supplementary. They are presented before derived units because they may be used in derived units. Thus, for practical purposes these supplementary units may be regarded as base units.

The supplementary quantities are plane angle and solid angle as given in Table 2-2 (Ref. 2).

TABLE 2-2
SUPPLEMENTARY UNITS

Quantity	Supplementary Unit	Symbol
plane angle	radian	rad
solid angle	steradian	sr

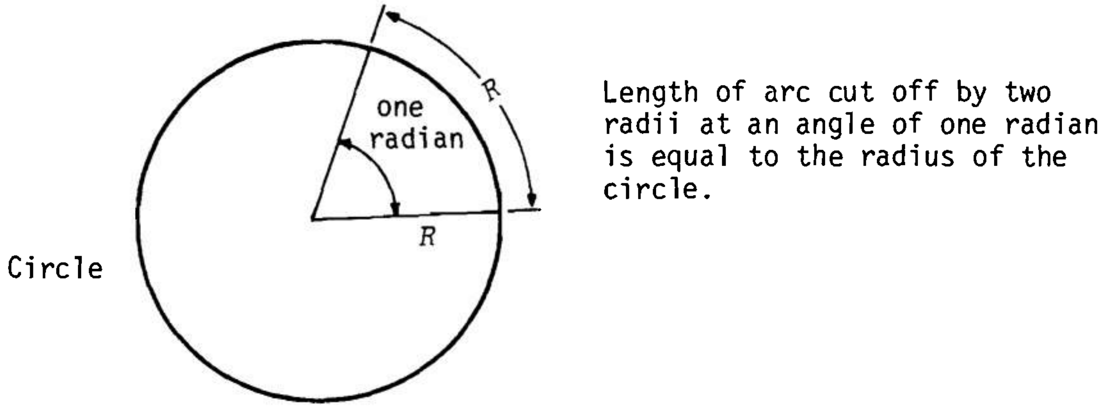
The radian and steradian are defined in International Standard ISO 1000 as follows (Ref. 2):

1. *radian.* The radian is the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius.

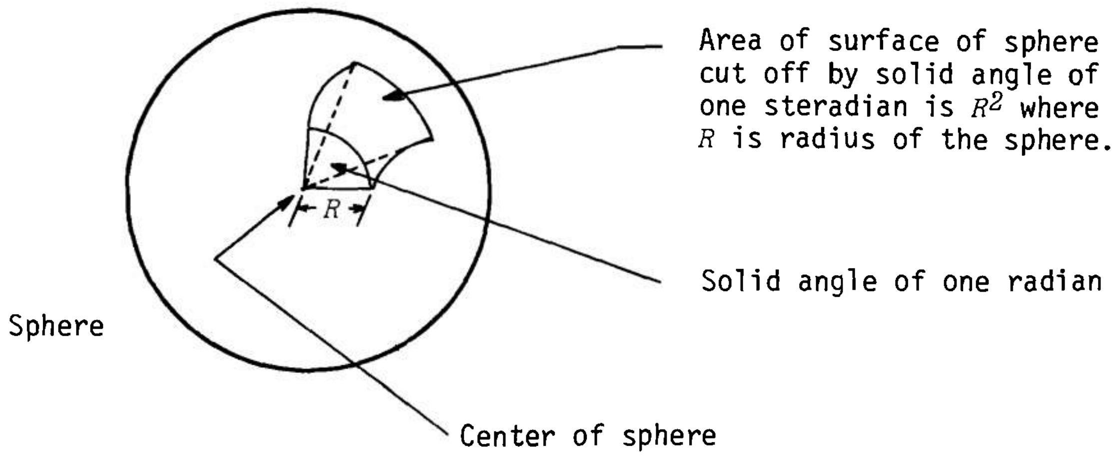
2. *steradian.* The steradian is the solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

These definitions are illustrated in Fig. 2-1. Note that there are 2π radians of plane angle in a complete circle and there are 4π steradians of solid angle in a complete sphere.

The use of degree (symbol °) and its decimal submultiples is permissible when use of the radian is not convenient. Solid angle always should be expressed in steradians (Ref. 5).



(A) Radian--construction of definition



(B) Steradian--construction of definition

Figure 2-1. Plane and Solid Angle SI Units

2-4 DERIVED UNITS

Derived units are units of physical quantities derivable from the set of base quantities (accepted as dimensionally independent), from the supplementary geometrical quantities, and from other previously formulated and accepted derived quantities. As the SI is a coherent system, and it is highly desirable that it remain such, all derived quantities and their units should be formulated such that no numerical factors are introduced.

Representative derived units are presented in Table 2-3 (Refs. 1, 2, 5, and 6). The base units and supplementary units are repeated here for convenience. References to other paragraphs of this handbook are included to allow rapid access to relevant information on style, use, and conversion of units. Entries in Table 2-3 are presented in the following groups:

1. Base units
2. Supplementary units
3. Units derived from base units
4. Derived units with special names
5. Other derived units
6. Non-SI units used with the SI
7. Experimentally determined units used with the SI
8. Units used with the SI for a limited time.

Units in Groups 6, 7, and 8 are included, again, for convenience.

TABLE 2-3
THE INTERNATIONAL SYSTEM OF UNITS (Refs. 1, 2, 5, 6)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
SI Base Units	length	metre	m		m
	mass	kilogram	kg		kg
	time	second	s		s
	electric current	ampere	A		A
	thermodynamic temperature	kelvin	K		K
	amount of substance	mole	mol		mol
	luminous intensity	candela	cd		cd
SI Supplementary Units	plane angle	radian	rad		
	solid angle	steradian	sr		
Units Derived from Base Units	area	square metre	m^2		m^2
	volume	cubic metre	m^3		m^3
	speed, velocity	metre per second	m/s		m/s
	acceleration	metre per square second	m/s^2		m/s^2
	angular velocity	radian per second	rad/s		rad/s
	angular acceleration	radian per square second	rad/s^2		rad/s^2

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Units Derived from Base Units (Cont'd)	wave number	1 per metre	1/m		1/m
	density, mass density	kilogram per cubic metre	kg/m^3		kg/m^3
	concentration (of amount of substance)	mole per cubic metre	mol/m^3		mol/m^3
	kinematic viscosity	square metre per second	m^2/s		m^2/s
	activity (radioactive)	1 per second	1/s		1/s
	specific volume	cubic metre per kilogram	m^3/kg		m^3/kg
	luminance	candela per square metre	cd/m^2		cd/m^2
Derived Units With Special Names	frequency	hertz	Hz		1/s
	force	newton	N		$kg \bullet m/s^2$
	pressure, stress	pascal	Pa	N/m^2	$kg/(m \bullet s^2)$
	energy, work quantity of heat	joule	J	$N \bullet m$	$kg \bullet m^2/s^2$
	power, radiant flux	watt	W	J/s	$kg \bullet m^2/s^3$
	electric charge	coulomb	C		$A \bullet s$

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Derived Units With Special Names (Cont'd)	electric potential potential difference electromotive-force	volt	V	W/A	$kg \bullet m^2/(s^3 \bullet A)$
	capacitance	farad	F	C/V	$A^2 \bullet s^4/(m^2 \bullet kg)$
	electric resistance	oh	Ω	V/A	$kg \bullet m^2/(s^3 \bullet A^2)$
	conductance	siemens	S	A/V	$A^2 \bullet s^3/(m^2 \bullet kg)$
	magnetic flux	weber	Wb	$V \bullet s$	$kg \bullet m^2/(s^2 \bullet A)$
	magnetic flux density	tesla	T	Wb/m^2	$kg/(s^2 \bullet A)$
	inductance	henry	H	Wb/A	$kg \bullet m^2/(s^2 \bullet A^2)$
	luminous flux	lumen	lm		$cd \bullet sr$
	illuminance	lux	lx	lm/m^2	$cd \bullet sr/m^2$
Other Derived Units	dynamic viscosity	pascal second	$Pa \bullet s$	$Pa \bullet s$	$kg/(m \bullet s)$
	moment of force	newton metre	$N \bullet m$	$N \bullet m$	$kg \bullet m^2/s^2$
	surface tension	newton per metre	N/m	N/m	kg/s^2
	heat flux density, irradiance	watt per square metre	W/m^2	W/m^2	kg/s^3

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Other Derived Units (Cont'd)	heat capacity, entropy	joule per kelvin	J/K	J/K	$kg \bullet m^2/(s^2 \bullet K)$
	specific heat capacity, specific entropy	joule per kilogram kelvin	$J/(kg \bullet K)$	$J/(kg \bullet k)$	$m^2/(s^2 \bullet K)$
	specific energy	joule per kilogram	J/kg	J/kg	m^2/s^2
	thermal conductivity	watt per metre kelvin	$W/(m \bullet K)$	$W/(m \bullet K)$	$kg \bullet m/(s^3 \bullet K)$
	energy density	joule per cubic metre	J/m^3	J/m^3	$kg/(m \bullet s^2)$
	electric field strength	volt per metre	V/m	V/m	$kg \bullet m/(s^3 \bullet A)$
	electric charge density	coulomb per cubic metre	C/m^3	C/m^3	$A \bullet s/m^3$
	electric flux density	coulomb per square metre	C/m^2	C/m^2	$A \bullet s/m^2$
	permittivity	farad per metre	F/m	F/m	$A^2 \bullet s^4/(m^3 \bullet Kg)$
	current density	ampere per square metre	A/m^2		A/m^2

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Other Derived Units (Cont'd)	magnetic field strength	ampere per metre	A/m		A/m
	permeability	henry per metre	H/m	H/m	$kg \bullet m/(s^2 \bullet A^2)$
	molar energy	joule per mole	J/mol	J/mol	$kg \bullet m^2/(s^2 \bullet mol)$
	molar entropy, molar heat capacity	joule per mole kelvin	$J/(mol \bullet K)$	$J/(mol \bullet K)$	$kg \bullet m^2/(s^2 \bullet K \bullet mol)$
	radiant intensity	watt per steradian	W/sr	W/sr	$kg \bullet m^2/(s^3 \bullet sr)$
	radiance	watt per square metre steradian	$W/(m^2 \bullet sr)$	$W/(m^2 \bullet sr)$	$kg/(s^3 \bullet sr)$
Non-SI Units Used With the SI	time	minute	min		60 s
	time	hour	h	60 min	3 600 s
	time	day	d	24 h	86 400 s
	plane angle	degree	°		$(\pi/180)$ rad
	plane angle	minute	'	$(1/60)°$	$(\pi/10\ 800)$ rad
	plane angle	second	"	$(1/60)'$	$(\pi/648\ 000)$ rad

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Non-SI Units Used With the SI (Cont'd)	volume	litre	ℓ	dm^3	10^{-3} m^3
	mass	tonne	t		10^3 kg
	Celsius Temperature	degree Celsius	°C		
	International Practical Kelvin (Celsius) Temperature Scale	kelvin (degree Celsius)			
Experimentally-Determined Units Used With the SI (Other experimentally-determined units are listed in Table 5-3.)	kinetic energy	electronvolt	eV	$1.602\ 19 \times 10^{-19}$ J	$1.602\ 19 \times 10^{-19}$ kg • m^2/s^2
	mass	unified atomic mass unit	u		$1.660\ 53 \times 10^{-27}$ kg
	length	astronomical unit	AU-English UA-French AE-German		$149\ 000 \times 10^6$ m
	length	parsec	pc	206 265 AU	$30\ 857 \times 10^{12}$ m
Units Used With the SI for a Limited Time	length	nautical mile			1 852 m
	speed	knot		nautical mile/h	(1 852/3 600)m/s
	length	ångström	Å	0.1 nm	10^{-10} m

TABLE 2-3. (cont'd)

UNIT CATEGORY	QUANTITY	UNIT NAME	UNIT SYMBOL	EXPRESSION IN TERMS OF OTHER UNITS	EXPRESSION IN TERMS OF SI BASE UNITS
Units Used With the SI for a Limited Time (Cont'd)	area	are	a		$10^2 m^2$
	area	hectare	ha		$10^4 m^2$
	area	barn	b		$10^{-28} m^2$
	pressure	bar	bar	10^5 Pa	10^5 kg/m • s^2
	pressure	standard atmosphere	atm	101 325 Pa	101 325 kg/m • s^2
	acceleration	gal	Gal	1 cm/s^2	10^{-2} m/s^2
	activity (radioactive)	curie	Ci		3.7 x10^{10}/s
	exposure (X or γ radiation)	roentgen	R	2.85 x 10^{-4}C/kg	2.85x10^{-4}A • s/kg
	dose (radioactive)	rad	rad, rd	10^{-2} J/kg	10^{-2} m^2/s^2

2-5 MULTIPLE AND SUBMULTIPLE PREFIXES

The 11th CGPM in 1960 adopted a series of names and symbols of unit prefixes to form decimal multiples and submultiples of SI units. In 1964, the 12th CGPM added prefixes for the submultiples 10^{15} and 10^{-18} (Ref. 1). The complete series is given in Table 2-4.

TABLE 2-4
SI PREFIXES

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

*To be avoided where possible.

To form a multiple of, for example, the metre, such that a unit 1000 times larger than the metre is formed, the prefix kilo is added forming kilometre (symbol km). The unit kilometre is 10^3 or 1000 times as large as the metre. The unit which is *smaller* than the second by a factor of 10^9 is the nanosecond (symbol ns), i.e., the nanosecond = 10^9 second. Conversions of multiple and submultiples are covered in Chapter 4. Rules for approved uses of multiple and submultiple prefixes are given in Chapter 3.

REFERENCES

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2. International Organization for Standardization, *SI Units and Recommendations for the Use of Their Multiples and Certain Other Units*, International Standard ISO 1000, ISO, Switzerland, 1973.
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*5. American National Standards Institute, American Society for Testing and Materials, *Standard for Metric Practice*, ASTM E 380, ANSI NY, January 1976.

6. National Aeronautics and Space Administration, *The International System of Units: Physical Constants and Conversion Factors*, by E. A. Mechtly, rev. ed., NASA Office of Technology Utilization, Scientific and Technical Information Division, Washington, DC, 1969.

*This publication is listed in the *DOD Index of Specifications and Standards* and is available without charge to US Government agencies through Naval Publications and Forms Center, 5801 Tabor Ave., Philadelphia, PA.

CHAPTER 3
GUIDELINES FOR USE AND APPLICATION OF THE INTERNATIONAL SYSTEM OF UNITS

Guidelines for use of the International System of Units are presented in this chapter. The information presented covers style, spelling, notation, selection of units, and selection of prefixes in using the SI and other units which can be used with the SI. Use of the SI in engineering drawings is covered in Chapter 6.

The information presented here is taken from both national and international standards and documents on the SI and its use. Where differences exist between U.S. and international recommended practices (there are surprisingly few), the U.S. recommended practice is given. The Standard for Metric Practice, ASTM E 380, (Ref. 1) which has been approved for use by the Department of Defense was one of the primary sources of information for this chapter.

It should be recognized that units, unit names and symbols, and practices have evolved to their present status and it is very likely that further changes will be made. It is important that scientists, engineers, and technicians stay informed of new standards and practices related to the SI. Additionally, in using existing documentation and data, it is important to determine those practices that were used therein and that could affect understanding and use of the data.

3-1 GENERAL USE OF SI

The units of the SI should be used in place of the units of all other systems of units; this implies the use of base units, supplementary units, and derived units with appropriate application of approved multiple and submultiple prefixes. In order to maintain the coherence of the SI, it is recommended that multiples and submultiples of SI units *not* be used in combinations to generate derived units and *not* be used in equations. Note that the kg is a base unit and is correctly used both in the formation of derived units and in equations.

3-2 MIXED UNITS

A mixed unit is a derived unit which contains units from two or more different systems of units or it is a unit containing different units for the same dimension. For example, mass per unit volume expressed in kilograms per gallon (kg/gal) uses units from the SI and U.S. customary units. Examples involving different units for the same dimension are: plane angle, 10 deg 15 min; mass, 12 lbm 12 ozm*. Mixed units such as these should be avoided. The correct units for these examples are given in Table 3-1.

TABLE 3-1
AVOID MIXED UNITS

Use	Do Not Use
kg/m^3	kg/gal
0.1789 rad or 10.25 deg	10 deg 15 min
12.75 lbm*	12 lbm 12 ozm*

3-3 USE OF PREFIXES

The use of approved prefixes as given in Table 2-4 is to eliminate insignificant digits and decimals, and to provide a convenient substitute for writing powers of ten. Typical examples are given in Table 3-2.

*See par. 4-3.2 for an explanation of pound-mass (lbm).

TABLE 3-2
USE OF PREFIXES

Quantities Without Use of Prefixes	Preferred Form
12 300 m = 12.3×10^3 m	12.3 km
0.0123 μA = 12.3×10^{-9} A	12.3 nA
0.000 219 kg = $219. \times 10^{-6}$ kg	219 mg

In selecting specific prefixes, it is recommended that multiples and submultiples of 1000 be used to the extent feasible. For example, the units of force which should be used most frequently are MN, kN, N, mN, etc.; and, in the case of length, km, m, mm, μm, nm, etc. should be used. Thus, unless a real advantage is realized, centimetre (cm) should be avoided. However, in the cases of area and volume used alone, cm^2 and cm^3 are frequently and acceptably used. Note that with units of order higher than one, such as m^2 and m^3, when a prefix is used as in cm^2 and cm^3, the power of 10 represented by the prefix is raised to the same order. Thus,

$$cm^3 = (cm)^3 = (10^{-2}\ m)^3 = 10^{-6}\ m^3 \tag{3-1}$$

In general, prefixes should be used such that the numerical part of the expression for a particular quantity is greater than 0.1 and less than 1000 except where certain prefixes have been agreed upon for specific situations. In tables and tabulations, the same prefix should be used for a quantity even though, as a result, tabulated numerical values fall outside the range 0.1 to 1000 (Ref. 1).

Double and hyphenated prefixes should never be used. As examples: use picofarad (pF) and not micromicrofarad (μμF); and, use gigawatt (GW) and not kilo-megawatt (kMW).

With the exception of the kilogram (kg), prefixes should not be used in the denominator of compound units. Prefixes may, however, be used in the numerator of compound units. Examples of such correct and incorrect uses of prefixes are given in Table 3-3 (Ref. 1).

TABLE 3-3
USE OF PREFIXES IN COMPOUND UNITS

Preferred	Not to be Used
N/m^2	N/cm^2 or N/mm^2
$kN \bullet s/m^2$ or $N \bullet s/m^2$	$kN \bullet s/mm^2$
$kW/(m \bullet K)$ or $W/(m \bullet K)$	$kW/(cm \bullet K)$
J/kg	mJ/g

3-4 STYLE

Use lower case letters for SI unit symbols unless the unit is derived from a proper name. Thus, use m for metre, kg for kilogram, and ℓ for litre, but use Hz for hertz derived from Hertz and N for newton derived from Newton. Note that the unabbreviated units in all cases whether derived from a proper name or not are not capitalized. With the exceptions of T for tera, G for giga, and M for mega the SI symbols for all prefixes are lower case letters.

Unabbreviated SI units form plurals in the same manner as all nouns. The SI symbols on the other hand are always written in a singular form. Periods are used after SI unit symbols only at the end of a sentence.*

In writing numbers having four or more digits, the digits should be placed in groups of three separated by a space and formed by counting both to the left and right of the decimal point. The groups of three im-

*The one exception is the abbreviation "in.", for inch, to avoid being identified as the preposition "in". However, should the possibility of error or confusion exist when abbreviations are used, follow the maxim "when in doubt, spell it out".

mediately to the left and right of the decimal point are not separated from the decimal point by a space. In the case of exactly four digits spacing is optional. This format of writing numbers facilitates both the reading of the numbers and also avoids confusion caused by the European use of commas to express decimal points (Ref. 2). These rules are illustrated in Table 3-4.

TABLE 3-4
NUMBER GROUPING IN SI

Use	Do Not Use
1234 or 1 234	1,234
12 345	12,345
12 345.678 91	12,345.67891

In cases where U.S. customary units must be given in texts or in small tables, it is permissible to give the SI equivalents in parentheses. However, when equations are written with U.S. customary units, confusion is avoided by not giving the SI equivalents in parentheses in the equation. Rather, it is preferred to restate the equation using SI units or to introduce a sentence, paragraph, or note stating precisely how to convert calculated results to the preferred SI units and giving the factors involved in that calculation.

In expressing derived unit abbreviations, the center dot with a space on each side is used to indicate multiplication and a slash is used to indicate division (Ref. 1). Examples are:

$$\mathrm{kg} \cdot \mathrm{m/s^2}$$
$$\mathrm{s} \cdot \mathrm{A/m^3}$$

It should be noted that errors and confusion can be introduced if the center dot is not used in forming derived units. As an example, consider a quantity encountered frequently in mechanics, moment of force, which is the product of force and distance. The derived unit for this quantity is the newton-meter; the symbole can be written N • m or m • N. Written without the center dot, Nm would be interpreted correctly as a newton-meter. But, if the order is changed to mN, the result is the millinewton!

Finally, in using the slash (/) to separate numerator and denominator terms in derived units it is possible to introduce ambiguities. For example, is the unit $\mathrm{m \cdot kg/s^3 \cdot K}$ in fact $\mathrm{m \cdot kg/(s^3 \cdot K)}$ or is it $\mathrm{m \cdot (kg/s^3) \cdot K}$? If all numerator terms were always placed to the left of the slash and all denominator terms placed to the right of the slash, and, if they were always interpreted in this manner, there would be no confusion. However, in the interest of avoiding errors it is suggested that parentheses be used with all denominator terms when there are two or more such terms. Thus for the given example, the units should be written $\mathrm{m \cdot kg/(s^3 \cdot K)}$ if second and kelvin belong in the denominator.

Another acceptable and unambiguous method of denoting numerator and denominator terms is to use positive and negative exponents. Using this notation, the previous example may be written:

$$\mathrm{kg \cdot m/s^2 = kg \cdot m \cdot s^{-2}}$$
$$\mathrm{c \cdot A/m^3 = c \cdot A \cdot m^{-3}}$$
$$\mathrm{m \cdot kg/(s^3 \cdot K) = m \cdot kg \cdot s^{-3} \cdot K^{-1}}$$

3-5 METRE/LITRE OR METER/LITER SPELLING

The "-re" spelling of metre and litre has not been accepted in the U.S. (Refs. 3 and 4). However, the ASTM *Standard for Metric Practice* has been approved for use by the Department of Defense and for listing in the DOD *Index of Specifications and Standards* (Ref. 1). The spelling metre/litre, is used in the ASTM *Standard for Metric Practice*. Also, the standard for dimensioning and tolerancing of engineering drawings that has been adopted by the Department of Defense, ANSI Y14.5-1973, uses the metre/litre spelling (Ref. 5). Thus, the metre-litre spelling is used in this handbook.

It is reiterated that this question of spelling has not been settled. It has been suggested, particularly in the U.S., that the spelling metre/litre will never be widely accepted. It has also been predicted that even if the "-re" spellings are accepted they will eventually be changed back to the "-er" spellings that we are accustomed to.

Finally, it should be noted that the guidelines for use of the International Systems of Units have been interpreted and modified for the U.S. by the National Bureau of Standards and, published in the June 19, 1975 Federal Register, explicitly state that both the "-re" and "-er" spellings for both metre and litre are acceptable.

3-6 TEMPERATURE

The correct temperature scale to be used in the SI is known as the International Thermodynamic Temperature Scale (Refs. 1, 2, and 6). The SI unit for temperature is the kelvin (K) which is used for both temperature and temperature differences and intervals. Note that the degree symbol (°) is *not* used with kelvin.

What was formerly called the centigrade scale and is now the Celsius temperature scale is acceptable because of the vast amount of data recorded using this scale and because of its broad use and familiarity in general (Ref. 1). The proper unit is the degree Celsius (°C). Note that the degree symbol (°) *is* used with the Celsius scale.

The symbols commonly used for temperatures are T when the Kelvin scale is used and θ or t when the Celsius scale is used. These symbols should be used only for temperature and not temperature differences. When differences or intervals are involved, notations such as $T_1 - T_2$ and $t_x - t_y$ or $\triangle T$ and $\triangle t$ avoid confusion and ambiguity. The conversion of temperature differences are simple:

$$1 \text{ Kelvin} = 1 \text{ degree Celsius} = 9/5 \text{ degree Fahrenheit} \tag{3-2}$$

and

$$\triangle T(\text{K}) = \triangle t(°\text{C}) = (5/9)\,\triangle t_F(°\text{F}) \tag{3-3}$$

The relationship between temperature T expressed in kelvins and temperature t expressed in degrees Celsius is:

$$T(\text{K}) = t(°\text{C}) + 273.15 \tag{3-4}$$

It is important to note that for a number of years the unit for thermodynamic temperature was the degree Kelvin and the symbol was °K (Ref. 6). The name for temperature interval or difference was the degree and the symbol was deg. This latter nomenclature, degree and deg, applied to both the thermodynamic temperature scale and the Celsius temperature scale. The 13th CGPM (1968) adopted the present name kelvin for thermodynamic temperature and approved the practice of using the same name and symbol for temperature and temperature interval.

Two additional scales are introduced here because a large amount of data has been recorded based upon these scales (Ref. 1). They are known as the International Practical Kelvin Temperature Scale of 1968 and the International Practical Celsius Temperature Scale of 1968. The units for these two scales are the kelvin (K) and the degree Celsius (°C), respectively. The symbols for temperature commonly used are T_{int} for the Practical Kelvin scale and t_{int} for the Practical Celsius scale. These temperature scales are defined by a set of interpolation equations based upon the reference temperatures given in Table 3-5. With respect to the International scales the kelvin and degree Celsius are identical in size and $T_{\text{int}} = t_{\text{int}} + 273.15$ exactly. The differences between the International Thermodynamic Temperature scale and the International Practical Temperature scale are significant only when extremely precise measurements are involved.

TABLE 3-5
REFERENCE TEMPERATURES* UPON WHICH PRACTICAL TEMPERATURE SCALES ARE BASED

	K	°C
Hydrogen, solid-liquid-gas equilibrium.............	13.81	-259.34
Hydrogen, liquid-gas equilibrium at 33 330.6 N/m^2 (25/76 standard atmosphere).......	17.042	-256.108
Hydrogen, liquid-gas equilibrium...................	20.28	-252.87
Neon, liquid-gas equilibrium.......................	27.102	-246.048
Oxygen, solid-liquid-gas equilibrium...............	54.361	-218.789
Oxygen, liquid-gas equilibrium.....................	90.188	-182.962
Water, solid-liquid-gas equilibrium................	273.16	0.01
Water, liquid-gas equilibrium......................	373.15	100.00
Zinc, solid-liquid equilibrium.....................	692.73	419.58
Silver, solid-liquid equilibrium...................	1235.08	961.93
Gold, solid-liquid equilibrium.....................	1337.58	1065.43

* Except for the triple points and one equilibrium hydrogen point (17.042 K) the assigned values of temperature are for equilibrium states at a pressure

$$p_o = 1 \text{ standard atmosphere } (101\ 325\ N/m^2).$$

3-7 NON-SI UNITS WHICH CAN BE USED WITH SI UNITS

There are a number of units which are not part of the SI which may be used with SI units, or, may be used with SI units for "a limited time" (Ref 2). Limited time is not specified in the literature. It can reasonably be assumed that this means that use of such non-SI units with the SI is acceptable only as long as it can be justified on the basis of realizing significant advantage. The period of time that such use will be acceptable, in the U.S., is a function of how rapidly metrication proceeds in this country and of the possible existence of and form of a national program of metrication. It can be argued that this situation will exist for from 10 to 30 yr into the future.

It is recommended that non-SI units be used only when there is a real advantage. When they are used in calculations or in any documentation, it should be noted that they are non-SI units and instructions on how to convert equations and numerical value to the SI should be given.

A number of the non-SI units which are accepted at least for the present are related to units of the SI by powers of ten (Ref 1). The bar — a unit of pressure equal to 100 kilonewtons per square metre (10^5 newtons

per square metre or 10^5 pascal) — is a convenient unit of pressure, particularly for meteorologists, because it is approximately equal to one atmosphere. Another example, from the field of geodetics, is the Gal (from Galileo), a unit of acceleration equal to 0.01 metre per second squared. While these units are not part of the International System of Units, they are metric units because they are related to base units by powers of ten. It is likely that one will encounter some confusion concerning their relationship to the SI.

One of the non-SI units, the litre, is particularly interesting because it is now being introduced to the public in the U.S. and is considered to be part of the SI even by some scientists and engineers. The most attractive features of the litre as a unit are: (1) it is only slightly larger than the quart, and (2) it is much easier to use than "one-thousandth of a cubic meter" — particularly in a grocery store.

A final note on these non-SI units concerns their use in derived units. When this is done, the system is no longer coherent and factors of proportionality are introduced. This can be illustrated by the derivation of a unit of force using the relationship force F equals mass M multiplied by acceleration A:

$$F = M A \tag{3-5}$$

If the units kilogram and Gal are used for mass and acceleration respectively, then the derived unit for force will, in this case, be the kilogram • Gal (symbol kg • Gal). Eq. 3-5 is perfectly valid using the units kilogram, Gal, and kilogram • Gal. Given values for any two of the quantities force, mass, and acceleration, the third can be determined. There are no numerical factors of proportionality introduced into Eq. 3-5 provided all quantities are expressed in the units kg, Gal, and kg • Gal. However, if data resulting from these calculations are to be used by an individual that is accustomed to working only with base units of the SI and other units derived from base units, then unnecessary complications will be introduced. This individual would have to determine what the units Gal and kg • Gal are in terms of base units. He would find that:

$$\text{Gal} = 10^{-2}\ \text{m/s}^2 \tag{3-6}$$

and

$$\text{kg} \bullet \text{Gal} = \text{kg} \bullet (10^{-2}\ \text{m/s}^2) = 10^{-2}\ \text{kg} \bullet \text{m/s}^2 = 10^{-2}\ \text{N} \tag{3-7}$$

Eqs. 3-6 and 3-7 allow conversion of the expressions in non-SI units to expressions in SI units. These equations also illustrate the advantages of maintaining a coherent system of units as defined in Chapter 2 and repeated here: "A coherent system of units is one in which all derived units can be expressed as products or ratios of the base units without the introduction of numerical factors." If the SI unit for acceleration, m/s^2, had been used in the original calculations in this example, there would be no numerical factors in Eqs. 3-6 and 3-7 and, in fact, there would be no reason for even considering these equations. All that has been said concerning non-SI units related to SI units by powers of ten is applicable to non-SI units in general.

3-8 GUIDELINES FOR SELECTION OF UNITS AND PREFIXES

The information presented in Table 3-6 is intended to serve as a guide in selecting units and prefixes. For each quantity in the table, the appropriate SI unit is given. The commonly used prefix for each unit also is given. For example, the SI unit for stress is the pascal with the symbol Pa or the newton per metre squared, N/m^2. The commonly used and recognized multiples and submultiples used for stress are: GPa, MPa or N/mm^2, and kPa. Note that one of the recognized units for stress, N/mm^2, does not follow the guidelines for the use of prefixes given in par. 3-3; i.e., prefixes should not be used in the denominator of compound units. This example illustrates the priority of recognized usage over the general guidelines.

Also included in Table 3-6, are those non-SI units that frequently are used and recognized in certain areas. For example, in the textile industry, the unit for linear density (kg/m in SI) that is commonly used is the tex. The tex is related to SI by the equation: 1 tex = 10^{-6} kg/m. As a further example, the table gives the units watt-hour (W • h), kW • h, etc., as the commonly used units for energy in the field of consumption of electrical energy.

While Table 3-6 is not exhaustive, it should prove to be useful to individuals working outside their field of expertise or experience. Also, it is emphasized that this information is intended to be a guide only and not to be interpreted as the only acceptable approach. In general, the most important consideration in selecting units is that of being understood and minimizing the possibility of errors.

REFERENCES

1. American National Standards Institute, American Society for Testing and Materials, *Standard for Metric Practice,* ASTM E 380, ANSI, NY, January 1976.
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6. NBS 330, *The International System of Units (SI),* Dept. of Commerce, National Bureau of Standards, April 1972.

TABLE 3-6
GUIDELINES FOR USE OF SI AND NON-SI UNITS (Ref. 2,

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
SPACE AND TIME			
length	m (metre)	km cm, mm, μm, nm	1 international nautical mile = 1852 m
area	m^2	km^2 dm^2, cm^2, mm^2	1 ha (hectare) = $10^4 m^2$ 1 a (are) = $10^2 m^2$
volume	m^3	dm^3, cm^3, mm^3	1 ℓ (litre) = 1 dm^3 (should not be used for high precision); 1 hℓ = $10^{-1} m^3$, 1 cℓ = $10^{-5} m^3$, 1 mℓ = $10^{-6} m^3$ = 1 cm^3
time	s (second)	ks ms, μs, ns	d (day), h(hour), min (minute) week, month, year are in common use
velocity	m/s		km/h (kilometre per hour) = (1/3.6) m/s 1 knot = 0.514 444 m/s
acceleration	m/s^2		
plane angle	rad (radian)	m rad, μrad	° (degree), '(minute), " (second); degree and grade (or gon) and decimal subdivisions recommended when radian is not convenient; 1 g (grade) = 1 gon = (π/200) rad
solid angle	sr (steradian)		
angular velocity	rad/s		
frequency	Hz (hertz)	THz, GHz, MHz, kHz	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
SPACE AND TIME (cont'd)			
rotational frequency	1/s		1/min (1 per minute); rpm or r/min (revolution/min), r/s (revolution/s) are widely used in specifying rotating machinery
MECHANICS			
mass	kg (kilogram)	Mg g, mg, μg	t (tonne) = 10^3 kg
linear density	kg/m	mg/m	1 tex = 10^{-6} kg/m commonly used in textile industry
momentum	kg • m/s		
moment of momentum, angular momentum	kg • m^2		
force	N (newton)	MN, kN mN, μN	
moment of force	N • m	MN • m, kN • m mN • m, μN • m	
pressure	Pa (pascal)	GPa, MPa, kPa, mPa, μPa	1 bar = 10^5 Pa; mbar, μbar
stress	Pa or N/m^2	GPa, MPa or N/mm^2, kPa	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
MECHANICS (cont'd)			
viscosity (dynamic)	Pa • s	mPa • s	P (poise), 1 cP = 1 mPa • s
viscosity (kinematic)	m^2/s	mm^2/s	St (stokes), 1 cSt = 1 mm^2/s
surface tension	N/m	mN/m	
energy, work	J (joule)	TJ, GJ, MJ, kJ, mJ	eV, GeV, MeV, keV are commonly used in atomic and nuclear physics; W • h (watt • hour), kW • h, MW • h, GW • h, TW • h are used for consumption of electric energy
power	W (watt)	GW, MW, kW, mW, μW	
HEAT			
thermodynamic temperature	K (kelvin)		
Celsius temperature	°C (degree Celsius)		The Celsius temperature t(°C) is equal to the difference between two thermodynamic temperatures: t(°C) = T(K) - 273.15

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
HEAT (cont'd)			
temperature interval	K (kelvin)		For temperature interval, °C may be used in place of K
linear expansion coefficient	1/K		°C may be used in place of K
heat, quantity of heat	J (joule)	TJ, GJ, MJ, kJ, mJ	
heat flow rate	W (watt)	kW	
thermal conductivity	$W \bullet (m^2 \bullet K/m)^{-1}$		°C may be used in place of K
coefficient of heat transfer	$W/(m^2 \bullet K)$		°C may be used in place of K
heat capacity	J/K	kJ/K	°C may be used in place of K
specific heat capacity	$J/(kg \bullet K)$	$kJ/(kg \bullet K)$	°C may be used in place of K
entropy	J/K	kJ/k	
specific entropy	$J/(kg \bullet K)$	$kJ/(kg \bullet K)$	
specific energy	J/kg	MJ/kg, kJ/kg	
specific latent heat	J/kg	MJ/kg, kJ/kg	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ELECTRICITY AND MAGNETISM			
electric current	A (ampere)	kA mA, μA, nA, pA	
electric charge	C (coulomb)	kC μC, nC, pC	1 A • h (ampere hour) = 3.6 kC
volume density of charge, charge density	C/m^3 (coulomb per metre cubed)	C/mm^3, MC/m^3, C/cm^3, kC/m^3 mC/m^3, $\mu C/m^3$	
surface density of charge	C/m^2 (coulomb per metre squared)	MC/m^2, C/mm^2, C/cm^2, kC/m^2 mC/m^2, $\mu C/m^2$	
electric field strength	V/m (volt per metre)	MV/m, kV/m, V/mm, V/cm, mV/m, μV/m	
electric potential potential difference electromotive force	V (volt)	MV, kV mV, μV	
displacement	C/m^2 (coulomb per metre squared)	C/cm^2, kC/m^2 mC/m^2, $\mu C/m^2$	
electric flux, flux of displacement	C (coulomb)	MC, kC mC	
capacitance	F (farad)	mF, μF, nF, pF	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ELECTRICITY AND MAGNETISM (cont'd)			
permittivity	F/m (farad per metre)	μF/m, nF/m, pF/m	
electric polarization	C/m^2 (coulomb per metre squared)	C/cm^2, kC/m^2 mC/m^2, $\mu C/m^2$	
electric dipole moment	C • m (coulomb metre)		
current density	A/m^2 (ampere per metre squared)	MA/m^2, A/mm^2, A/cm^2, kA/m^2	
linear current density	A/m (ampere per metre)	kA/m, A/mm, A/cm	
magnetic field strength	A/m (ampere per metre)	kA/m, A/mm, A/cm	
magnetic potential difference	A (ampere)	kA mA	
magnetic flux density, magnetic induction	T (tesla)	mT, μT, nT	
magnetic flux	Wb (Weber)	mWb	
magnetic vector potential	Wb/m (weber per metre)	kWb/m, Wb/mm	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ELECTRICITY AND MAGNETISM (cont'd)			
self inductance, mutual inductance	H (henry)	mH, μH, nH, pH	
permeability	H/m (henry/metre)	μH/m, nH/m	
electromagnetic moment, magnetic moment	$A \bullet m^2$ (ampere metre squared)		
magnetization	A/m (ampere per metre)	kA/m, A/mm	
magnetic polarization	T (tesla)	mT	
magnetic dipole moment	$N \bullet m^2/A$ or Wb/m (weber per metre)		
resistance	Ω (ohm)	GΩ, MΩ, kΩ mΩ, μΩ	
conductance	S (siemens)	kS mS, μS	
resistivity	Ω • m (ohm metre)	GΩ • M, MΩ • m, kΩ • m, Ω • cm, mΩ • m, μΩ • m, nΩ • m	$\mu\Omega \bullet cm = 10^{-8}\ \Omega \bullet m$ and $\Omega \bullet mm^2/m = \mu\Omega \bullet m$ are also used
conductivity	S/m (siemens per metre)	MS/m, kS/m	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ELECTRICITY AND MAGNETISM (cont'd)			
reluctance	1/H (1 per henry)		
permeance	H (henry)		
impedance, modulus of impedance, reactance, resistance	Ω (ohm)	MΩ , kΩ mΩ	
admittance, modulus of admittance, susceptance, conductivity	S (siemens)	kS mS, µS	
active power	W (watt)	TW, GW, MW, kW mW, µW, nW	"apparent power" in V • A (volt amperes) and "reactive power" in var (vars) = W are frequently used in electric power industry
LIGHT AND RELATED ELECTROMAGNETIC RADIATION			
wavelength	m (metre)	nm, pm	1 Å (ångström) = 10^{-10} m = 0.1 nm = 10^{4} µm
radiant energy	J (joule)		
radiant flux, radiant power	W (watt)		

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
LIGHT AND RELATED ELECTROMAGNETIC RADIATION (cont'd)			
radiant intensity	W/sr (watt per steradian)		
radiance	W/(sr• m^2) (watt per steradian metre squared)		
radiant exitance, irradiance	W/m^2 (watt per metre squared)		
luminous intensity	cd (candela)		
luminous flux	lm (lumen)		
quantity of light	lm•s (lumen second)		1 lm•h (lumen hour) = 3 600 lm•s
luminance	cd/m^2 (candela per metre squared)		
luminous exitance	lm/m^2 (lumen per metre squared)		
illuminance	lx (lux)		
light exposure	lx•s (lux second)		
luminous efficacy	lm/W (lumen per watt)		

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ACOUSTICS			
period, periodic time	s (second)	ms, μs	
frequency	Hz (hertz)	MHz, kHz	
wavelength	m (metre)	mm	
density, mass density	kg/m^3 (kilogram per metre cubed)		
static pressure, (instantaneous) sound pressure	Pa (pascal)	mPa, μPa	dyn/cm^2
(instantaneous) sound particle velocity	m/s (metre per second)	mm/s	
(instantaneous) volume velocity	m^3/s (metre cubed per second)		
speed of sound	m/s (metre per second)		
sound energy flux, sound power	W (watt)	kW mW, μW, pW	

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
ACOUSTICS (cont'd)			
sound intensity	W/m^2 (watt per metre squared)	mW/m^2, $\mu W/m^2$, pW/m^2	
specific acoustic impedance	$Pa \bullet s/m$ (pascal second per metre)		
acoustic impedance	$Pa \bullet s/m^3$ (pascal second per metre cubed)		
mechanical impedance	$N \bullet s/m$ (newton second per metre)		
sound pressure level (SPL)			dB (0 dB SPL = 20 $\mu N/m^2$)
sound reduction index, sound transmission loss			dB
equivalent absorption area of a surface	m^2 (metre squared)		
reverberation time	s (second)		

TABLE 3-6 (cont'd)

QUANTITY	SI UNIT	COMMONLY USED MULTIPLES AND SUBMULTIPLES	NON-SI UNITS COMMONLY USED/MULTIPLES AND SUBMULTIPLES/REMARKS
PHYSICAL CHEMISTRY AND MOLECULAR PHYSICS			
amount of substance	mol (mole)	kmol mmol, μmol	
molar mass	kg/mol (kilogram per mole)	g/mol	
molar volume	m^3/mol (metre cubed per mole)	dm^3/mol, cm^3/mol	
molar internal energy	J/mol (joule per mole)	kJ/mol	
molar heat capacity	J/(mol • K) (joule per mole kelvin)		
molar entropy	J/(mol • K) (joule per mole kelvin)		
concentration	mol/m^3 (mole per metre cubed)	mol/dm^3, kmol/m^3	mol/ℓ (mole per litre)
molality	mol/kg (mole per kilogram)	mmol/kg	
diffusion coefficient, thermal diffusion coefficient	m^2/s (metre squared per second)		

CHAPTER 4
CONVERSION OF UNITS

In this handbook, dimensional analysis is used in the conversion of a quantity expressed in one system of units to the same quantity expressed in another system of units. This application of dimensional analysis can signficantly reduce errors made in the conversion of units and is particularly effective in those cases where one has no intuitive feel for the relative magnitudes of the units involved (Refs. 1, 2).

Along with the presentation of the method of converting units, examples are given of conversions between various systems of units with emphasis on conversion to the SI. Emphasis is on the "how to" aspects of such conversions and on a variety of potential problems which can be encountered in making conversions. Chapter 7 contains additional examples using data and calculations taken from US Army Materiel Command Engineering Design Handbooks.

The concept of and the application of significant digits in conveying accuracy of measurements and estimates is introduced. Specifically, accuracy in the conversion of units is considered in detail. Other specific subjects covered in this chapter are: (1) mass, force and weight; (2) temperature conversions; (3) electromagnetic units; and (4) equations. In each case, fundamental concepts and background material are presented to the extent necessary for understanding what is involved in the conversion of units. There is no substitute for understanding in the general case.

4-1 CONVERSION OF SINGLE QUANTITIES

In general, the expression for a quantity such as length is an expression of a measurement, estimate, requirement, or calculated value of a physical quantity. It is emphasized that such an expression, for example 5.63 ft, represents a physical quantity. Further, this expression consists generally of a numerical part and a unit. The numerical part of the expression tells how many of the units are equivalent to the quantity measured. The units are themselves a very specific and standardized measurement.

When we make a conversion from one system of units to another, we do not change the physical quantity which has been measured; that is fixed. What we do change, in general, is the numerical part of the expression of the measurement and the units upon which the measurement is based. That is, when we convert the measurement 1 ft to 0.3048, we have not changed the length of the quantity measured. What is different is that the unit of measurement, the metre in this case, to which we have converted is approximately 3.28 times as long as the original unit of measurement, the foot. Again, the physical length, 1 ft, is physically the same as the length 0.3048 m.

Note that in converting the measurement 1 ft to 0.3048 m there is no conversion of dimensions. Dimension refers here to length and our measurement before and after conversion is one along the dimension of length. Again, what has been changed is the unit of measurement, not the dimension of the measurement.

Consider the quantity:

$$1.234 \text{ in.}$$

Assume that we wish to convert this length to a length in the SI system expressed in metres. From the listing of unit equalities in Table 5-1 we obtain the following equality:

$$1 \text{ in.} = 0.0254 \text{ m} \tag{4-1}$$

Dividing both sides of this equality (or equation) by 1 in. we obtain:

$$1 = \frac{0.0254 \text{ m}}{1 \text{ in.}} \tag{4-2}$$

This quantity has the dimensions of length divided by length and, therefore, it is a dimensionless quantity. It is a ratio having the units metres per inch; the numerical value 0.0254 and the units together are a unit

factor equal to one. Thus, we can multiply the original length by this unit factor without changing it as follows: *

$$1.234\ \text{in.} = 1.234\ \text{in.} \times \frac{0.0254\ \text{m}}{1\ \text{in.}} \tag{4-3}$$

Make the assumption at this point that the "common factor", inch, in the denominator and numerator of this fraction can be cancelled. Note that although strictly speaking inch is not a common factor, if we replace inch by 1 in. (which is entirely permissible) then it becomes a common factor and the rules of algebra may be applied with complete validity. Thus we obtain the following:

$$1.234 \times 0.0254\ \text{m} = 0.0313\ \text{m} \tag{4-4}$$

which concludes that the conversion of a length of 1.234 in. to the SI system of units gives 0.0313 m.

By using unit equalities in converting units, it is unlikely that mistakes will occur if one does not make algebraic or arithmetic mistakes. For example consider the given example again. From Eq. 4-1, the following unit factor also can be formed:

$$1 = \frac{1\ \text{in.}}{0.0254\ \text{m}} \tag{4-5}$$

Multiplying the original quantity, 1.234 in., by this unit factor gives:

$$1.234\ \text{in.} \times \frac{1\ \text{in.}}{0.0254\ \text{m}} = 48.583\ \frac{\text{in.}^2}{\text{m}} \tag{4-6}$$

This is valid. The quantity has the dimensions length^2 divided by length or simply length. Physically, 48.583 in.^{2}/m is the same quantity we started with. The problem is that the unit in.^{2}/m is not very useful. The important point here is that if one keeps track of units in the conversion of units (and, in fact, in all calculations) errors can be minimized.

As a further example, consider that a 3/4-hp motor has failed and must be replaced. Assume further that commercially available electric motors are rated in kilowatts. Thus, our conversion is from horsepower to kilowatt ratings. The quantity we wish to convert is:

$$0.75\ \text{hp}$$

From the table of unit equalities we obtain:

$$1\ \text{U.S. hp} = 745.699\,87\ \text{W} \tag{4-7}$$

which can be rewritten in the following form:

$$\frac{745.699\,87\ \text{W}}{1\ \text{U.S. hp}} = 1 \tag{4-8}$$

The original quantity is multiplied by this unit factor to obtain:

$$0.75\ \text{hp} \times \frac{745.699\,87\ \text{W}}{1\ \text{U.S. hp}} = 559\ \text{W} \tag{4-9}$$

Note that we have retained only three significant figures because it is likely that electric motors are not specified in increments as small as fractions of a watt (or even watts). We still must convert watts to kilowatts. From Table 2-4, the prefix kilo- increases the size of a unit by 10^3. Thus,

$$1\ \text{kW} = 10^3\ \text{W} \tag{4-10}$$

Since we know that a kilowatt is a larger unit than a watt, then, in an equality relating these two units, there must be more watts than kilowatts. (Such seemingly obvious statements may seem trivial. But, making such quick mental checks can save much time and costs in reducing mistakes.) Eq. 4-10 gives the following unit factor:

$$1 = \frac{1\ \text{kW}}{10^3\text{W}} \tag{4-11}$$

* According to the rules of algebra, multiplication by 1 does not change the value of the original quantity.

And, the final step in the conversion is:

$$559\ \mathrm{W} \times \frac{1\ \mathrm{kW}}{10^3\ \mathrm{W}} = 0.559\ \mathrm{kW} \tag{4-12}$$

At this point, we would specify the purchase of an electric motor with the smallest kilowatt rating available which is equal to or exceeds 0.559 kW (e.g., 0.75 kW). Of course, other specifications for the motor would include shaft speed. mounts and other features, environmental exposure, and functional requirements.

While the examples given in this handbook make use only of the tables of unit equalities given in Chapter 5, unit conversion factors are given in other sources in formats which if not used carefully can result in errors. As an example, consider the conversion of 1.8 gauss to tesla — few of us have a "feel" for the relative magnitude of these two units. A number of references give conversion factors for magnetic flux density and other units in the format of Table 4-1 (Ref. 3).

TABLE 4-1
ENTRY FROM TYPICAL TABLE OF CONVERSION FACTORS

To convert from	to	Multiply by
•	•	•
•	•	•
•	•	•
gauss	tesla	−04 1.00*
•	•	•
•	•	•
•	•	•

The entry in Table 4-1 reads: "To convert gauss to tesla multiply by 1.00×10^{-4}." The asterisk (*) means the conversion is an exact one. To use the table we simply multiply 1.8 gauss by 1.00×10^{-4} to obtain the result 1.8×10^{-4} tesla. This *is* the *correct* result.

However, consider what can happen. Suppose we wish to set up an equality between gauss and tesla to use in a complex conversion. The first step, seemingly logical, is to write the following:

NOT CORRECT $$1\ \text{gauss} \times (1.00 \times 10^{-4}) = 1\ \text{tesla} \tag{4-13}$$

From this we obtain:

NOT CORRECT $$1 = \frac{1\ \text{tesla}}{10^{-4}\ \text{gauss}} \tag{4-14}$$

and convert the original quantity in the following manner:

NOT CORRECT $$1.8\ \text{gauss} \times \frac{1\ \text{tesla}}{10^{-4}\ \text{gauss}} = 1.8 \times 10^{+4}\ \text{tesla!} \tag{4-15}$$

This *is* the *wrong* answer. *This kind of error is very unlikely if tables of unit equalities are used.*

By adhering to the procedure of working from the unit-equality equation, the correct conversion value would have resulted; i.e.,

1. From the listing of unit equalities in Table 5-1:

$$1\ \text{gauss} = 1.00 \times 10^{-4}\ \mathrm{T}$$

or

$$1 = \frac{1.00 \times 10^{-4}\ \mathrm{T}}{1\ \text{gauss}}$$

2. Multiply the original quantity by this unit factor:

$$1.8\ \text{gauss} \times \frac{1.00 \times 10^{-4}\ \mathrm{T}}{1\ \text{gauss}} = 1.8 \times 10^{-4}\ \mathrm{T}\ \text{(the \textit{correct} value)}$$

As a final point related to not making mistakes it is reiterated that converting units does not change the dimensions of a quantity. Thus, in the examples given, length was converted to length, power to power, etc. As examples of converting the units of more complex derived quantities are considered, this matter of not changing the dimensions of a quantity becomes more important.

4-2 ACCURACY IN CONVERTING UNITS

Before proceeding with the methods of and problems encountered in the conversion of units, the subject of rounding will be dealt with. This will encompass significant digits, accuracy, rules for rounding, significant digits in computation, and how to handle significant digits and rounding in the conversion of units.

It is emphasized at the beginning of this paragraph that logic and reason must be applied at all times in the conversion of units and, particularly, in the areas of accuracy and significance of numbers. The rules presented here are not binding; there is no substitute for common sense.

4-2.1 SIGNIFICANT DIGITS

The numbers considered here are in general estimates, measurements, and specifications of physical quantities. They are, in general, *not* exact measurements, abstractions, or counts.

The concept of significant digits involves the accuracy of these numbers — measurements and estimates. The significant digits in a number are those digits that have numerical significance with respect to the physical object measured or estimated. Any digit that is necessary to define the specific quantity represented by a number is said to be significant.

The length of a football field measured to the nearest foot is 300 ft. Each of the digits is significant including the two zeros. The number 300, in this case, has three significant digits because the measurement was accurate to the nearest foot. If the field were 301 ft long, then a measurement accurate to the nearest foot would have yielded a measured value of 301 ft. The length of the same football field measured to the nearest metre is 91 m. Again each of these digits is significant, but, in this case, the number has only two significant digits. This results because a measurement to the nearest metre is less accurate than a measurement to the nearest foot.

Consider the measurement of a football field a third time. Measured accurately — roughly, to the nearest foot using a metre stick marked at tenths of a metre — the most likely measured value will be 91.4 m. This value has three significant digits. Thus, the accuracy of a measurement and not the units employed determines the number of significant digits in a measured value.* This last example actually illustrates the situation of converting a measurement in feet to an expression in metres.

In the case of a football field measurement it is easy to identify the significant digits. This is not always the case. Consider the value 4 in. It may be known that there is one significant digit. But, in some cases, the intended quantity may be 4.0, 4.00, or 4.000 0, etc. The latter of these, 4.000 0 in., implies 4 in. measured to the nearest ten-thousandth of an inch. Accuracy must be specified in some manner either as accuracy or as number of significant digits.

The measurement of a football field to the nearest foot implies an accuracy of ± 0.5 ft. What this means is that as a result of the measurement it is known that the length of the field is 100 ft ± 0.5 ft which means that the field length is between 299.5 ft and 300.5 ft. The accuracy of this measurement can also be expressed as a percentage: ± (0.5 ft/300. ft) × 100% or ± 0.167%. In the case of the measured value 4.0000 in., having five significant digits, the implied accuracy is ± 0.000 05 in. This can be expressed as ± (0.000 05 in./4.0000 in.) 100% which equals ± 0.00125%.

Note that zeros may be either significant digits or they may only indicate the magnitude of a number. In the date, 1970, the zero is a significant digit. The population of the U.S. in 1960 rounded to the nearest thousand, 179 323 000, the zeros indicate magnitude but are not significant digits. The zeros in 0.001 32 are not significant digits.

Finally, consider exact counts of objects, such as 4 trucks, $38.25, and 31 transistors. These numbers can be treated as though they have an infinite number of significant digits.

*This is not intended to imply that number of significant digits is independent of units selected.

4-2.2 ROUNDING

Rounding is a process of reducing the number of digits in a number. This reduction can involve simple removal of digits as in the following:

12.312 rounded to 12.3

Or, digits may be replaced by nonsignificant zeros as in:

12 321.4 rounded to 12 300.

In rounding the number 12 345 to three significant digits, for example, the digits 4 and 5 are replaced by zeros. Digit 4 will be referred to as the *first* digit removed; the digit 3 will be referred to as the *last* digit retained. The rules for rounding are given in the paragraphs that follow (Ref. 4).

If the first digit discarded is *less* than 5, the last digit retained is not changed. Examples are:

a. 649 238 rounded to 4 significant digits is 649 200.
b. 12.039 29 rounded to 5 significant digits is 12.039.
c. 100.098 rounded to 3 significant digits is 100.

If the first digit removed is *greater* than 5, or if it is a 5 followed by at least one digit not a zero, then the last digit retained is increased by one unit. Examples are:

a. 160.934 rounded to 3 significant digits is 161.
b. 109.955 01 rounded to 5 significant digits is 110.00.
c. 306.67 rounded to 4 significant digits is 306.7.

When the first digit removed *is* 5, followed only by zeros, the last digit retained should increase by one unit if it is an odd number and it should not be changed if it is an even number. Examples are:

a. 123.5 rounded to 3 significant digits is 124.
b. 0.025 rounded to 1 significant digit is 0.02.
c. 99.95 rounded to 3 significant digits is 100.

4-2.3 SIGNIFICANT DIGITS IN CALCULATIONS

In calculations involving measurements and estimates, it is important to understand how to determine the number of significant digits in the result and to indicate this by rounding or notes. The need for this consideration can be illustrated by the following calculation:

368 000 000	3 significant digits
− 468.2	4 significant digits
367 999 531.8	

The result obtained appears to represent a very accurate measurement; in fact, it does not. The number 368 000 000 represents a quantity *between* 367 500 000 and 368 500 000. (This can be written 368 000 000 ± 500 000). That is, any number between these limits rounded to three significant digits would be 368 000 000. The result of subtracting 468.2 from this number obviously cannot be more precise than the number itself. Note that if the result is rounded to 3 significant digits, one obtains 368 000 000! Rules for calculations involving different numbers of and positions of significant digits are given in the paragraphs that follow (Ref. 4).

The rule for addition and subtraction is that the answer should contain no significant digits farther to the right than occurs in the least accurate number involved in the calculation. Consider addition of the following numbers:

163 000 000	3 significant digits
217 880 000	6 significant digits
96 432 768	8 significant digits

The least accurate of these numbers is 163 000 000. The last significant digit, 3, represents 3 000 000 ± 500 000. It is important to note that zeros to the right of the last nonzero digit can be significant; e.g., the last significant digit in 217 880 000 is the first zero to the right of the nonzero digit and represents 0 ± 500. (It is known that there are six significant digits because this fact was stated previously in the table. When zeros are significant to the left of the decimal point, it must be noted in some manner; when zeros are significant to the right of the decimal point, this is not necessary.)

The result of adding these numbers then cannot have a significant digit to the right of the 3 in the first number; i.e., the 10^6 or millions position. The numbers can be added to obtain 477 317 768. Rounded to the millions digit, the correct result is 477 000 000 and has three significant digits.

Time can be saved if the following method is used. Each of the numbers can be rounded to one significant digit farther to the right than the last significant digit in the least accurate number. In the given example this results in:

$$\begin{array}{r} 163\ 000\ 000 \\ 217\ 900\ 000 \\ +\ \ 96\ 400\ 000 \\ \hline 477\ 300\ 000 \end{array}$$

The result of adding these numbers is then rounded to 477 000 000. (With most scientists, engineers, and technicians using electronic calculators, the second method probably requires more time.)

In the case of multiplication and division, the product or quotient can have no more significant digits than the smaller number of significant digits in the numbers entering the calculation. Examples are:

a. $168.32 \div 0.12 = 1402.67$ rounded to 1400

b. $27.1 \div 6832.4 = 0.003\ 966\ 395$ rounded to 0.003 97

c. $4 \times 73.135 = 292.54$ rounded to 300

It is reiterated here that one always should know what numbers represent and what accuracy should be inferred. In the last example, the assumption was made that 4 involved only one significant digit. If it contains more than that it should be written: 4.0, 4.00, 4.0000, etc., whatever is appropriate.

4-2.4 ACCURACY IN THE CONVERSION OF UNITS

The conversion of units, with the exception of temperature, involves multiplication and division. A quantity expressed in one set of units is multiplied by or divided by a conversion factor to give a new expression generally with SI units. It is important that, following the conversion of units, the accuracy implied by the new expression be the same as that of the original expression.

Consider conversion to SI units of the volume 1.5 yd^3. From the table of unit equalities,

$$1\ yd^3 = 7.645\ 549 \times 10^{-1}\ m^3 \tag{4-16}$$

The unit factor for conversion is:

$$1 = \frac{0.764\ 554\ 9\ m^3}{yd^3} \tag{4-17}$$

and the conversion is:

$$1.5\ yd^3 \times \frac{0.764\ 554\ 9\ m^3}{yd^3} = 1.146\ 832\ 35\ m^3 \tag{4-18}$$

If one is greatly concerned with accuracy, the result is not bad. It implies accuracy to one part in 10^8; and with an electronic calculator, it is easy to obtain. But, it very likely does not have any significance.

If one is specifying an amount of concrete to be ordered, a supplier would not know what to do with 1.146 832 35 m^3 even if he were equipped to deliver in units of cubic metres. Assuming that suppliers had the capability to deliver quantitites of concrete in cubic metres, one would probably order 1.2 or 1.25 m^3 if he had been conservative.

On the other hand, if one were specifying volume of a fuel tank for a rocket engine, the specification would, in fact, have to be very accurate. (It is very doubtful that cubic yards would have been used in such a calculation in the first place.)

Thus, in converting units associated with estimates, measurements, and specifications it is important that the results imply the required accuracy but no more than is required. Precision is expensive. Rules for selecting the appropriate number of significant digits following change of units are presented in the paragraphs that follow. Knowledge of what one is working with and common sense are as important as the rules.

Consider the conversion of the length 1.1875 in. to millimetres. It may be noted that this is the exact decimal equivalent of 1-3/16 in. We will assume that an investigation of the situation reveals that 1.1875 in. is a measured value obtained with a scale marked in increments of 1/16 in. Thus the measurement probably

involes an accuracy of $\pm 1/2 \times 1/16$ in. or ± 0.031 in. There is thus no justification for retaining digits to the right of the one hundredth position; i.e., the decimal equivalent of 1-3/16 in. should be written 1.19 in. Note that 1.19 in. is equivalent to 1.19 ± 0.005 in. The conversion of 1.19 in. to millimetres is as follows. From Table 5-1:

$$1 \text{ in.} = 25.4 \text{ mm} \tag{4-19}$$

and the unit conversion factor is:

$$1 = \frac{25.4 \text{ mm}}{\text{in.}} \tag{4-20}$$

The converted value is:

$$1.19 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 30.226 \text{ mm} \tag{4-21}$$

The last significant digit in the result should give the same accuracy (or slightly better) as the accuracy of the original quantity) i.e., ± 0.031 in. Converting this gives:

$$\pm 0.031 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = \pm 0.787 \text{ mm} \tag{4-22}$$

Note that a unit in the one-tenth position will give better than the required accuracy. Thus, the converted value should be rounded off to 30.2 mm.

In general, following conversion to SI units, the converted value should be rounded to the minimum number of significant digits such that a unit of the last significant digit in the result is equal to or smaller than the converted value of a unit of the last significant digit in the original expression (Ref. 4). The following examples illustrate this:

Example No. 1: Convert 2.6×10^4 Btu (ISO/TC 12) to joules.

a. Assume 2 significant digits.

b. From Table 5-1: 1 Btu = $1.055\ 06 \times 10^3$ J

c. Convert: $2.6 \times 10^4 \text{ Btu} \times \dfrac{1.055\ 06 \times 10^3 \text{ J}}{\text{Btu}} = 2.743156 \times 10^7 \text{ J}$

d. Convert a unit in the position of the last significant digit:

$$0.1 \times 10^4 \text{ Btu} \times \frac{1.055\ 06 \times 10^3 \text{ J}}{\text{Btu}} = 0.105\ 506 \times 10^7 \text{ J}$$

e. Thus the converted value can be rounded to 2.7×10^7 J = 27 MJ. Note that 0.1×10^7 J is less than $0.105\ 506 \times 10^7$ J.

Example No. 2: Convert 3.00 fluid ounces (U. S.) to metre^3.

a. There are 3 significant digits.

b. From Table 5-1: 1 fluid ounce = $2.957\ 353 \times 10^{-5}$ m^3

c. Convert: $3.00 \text{ fluid ounces} \times \dfrac{2.957\ 353 \times 10^{-5} \text{ m}^3}{\text{fluid ounce}} = 8.872\ 059 \times 10^{-5} \text{ m}^3$

d. Convert unit in position of last significant digit:

$$0.01 \text{ fluid ounce} \times \frac{2.957\ 353 \times 10^{-5} \text{m}^3}{\text{fluid ounce}} = 0.029\ 573\ 53 \times 10^{-5} \text{ m}^3$$

e. The converted value can be rounded to: 8.87×10^{-5} m^3

f. Note that since 1 ℓ = 1 dm^3 = 10^{-3} m^3, this can be written: 0.0887 ℓ.

The following is a rule specific for the conversion of inch-values to millimetre-values (Ref. 4): "The converted expression in millimetres should have one more significant digit than the expression in inches when the first digit in the millimetre-value is smaller than or equal to that in the inch-value. If the first digit in the

millimetre-value is larger than that in the inch-value, the two values should have the same number of significant digits." Examples follow:

Example No. 3: Convert 32.93 in. to millimetres.

a. From Table 5-1: 1 in. = 25.4 mm

b. Convert: $32.93 \text{ in.} \times \dfrac{25.4 \text{ mm}}{\text{in.}} = 836.42 \text{ mm}$

c. 8 is larger than 3; therefore, round result to 4 significant digits: 836.4 mm

Example No. 4: Convert 5.013 in. to millimetres.

a. From Table 5-1: 1 in. = 25.4 mm

b. Convert: $5.013 \text{ in.} \times \dfrac{25.4 \text{ mm}}{\text{in.}} = 127.33$

c. 1 is less than 5; therefore, round to five significant digits; the result has five significant digits and therefore does not require rounding.

The subject of precision will reoccur throughout the remainder of this handbook. Additional information is introduced as required. The subjects of tolerances and dimensions are covered in Chapter 6, Engineering Drawings.

4-3 MASS, FORCE, AND WEIGHT

Conversions and, in general, working with quantities of mass, force, and weight and their units in different systems of units are complex, and errors are easily and frequently made. In order to explain and illustrate the relationships between the different units involved, it is necessary to consider some of the fundamentals of systems of units which may be encountered in the general area of mechanics. The concepts of force, weight, and mass are reviewed briefly in the paragraphs that follow. These considerations are followed by examples illustrating conversion and use of the units involved.

4-3.1 BASIC CONCEPTS

By a purely experimental process, Galileo and Newton were led to an important property of the motion of bodies; this property is concisely stated in Newton's first principle (Ref. 6):

"A particle (body) left to itself will maintain its velocity unchanged."

In other words, a moving object will continue moving at constant speed and in the same direction, or, it will remain at rest if it not influenced by any external factors.

The property of a body which results in its remaining at rest or at constant velocity is called inertia. The measure of inertia is mass*. The larger the mass of a body, the more "difficult" it becomes to change the motion of that body; i.e., more force must be applied, or more energy must be used in causing that change in motion.

The statement that "more force" (or force in general) must be applied to change the motion of (accelerate) a body reflects the basic concept of force**. The relationship between mass and force as con-

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*A rigorous definition of mass is (Ref. 6):

The mass m of a general body is defined by the equation:

$$m = \left(\frac{a_s}{a}\right) m_s$$

when the general body interacts (i.e., collides) with a standard body of mass m_s with resulting acceleration a of the general body and acceleration a_s of the standard body. The standard for the unit of mass, the kilogram (kg) is a particular cylinder of platinum-iridium alloy preserved in a vault at Sèvres, France, by the International Bureau of Weights and Measurements.

**Force can be defined in the following manner (Ref. 6):

When two bodies interact such that their state of motion is changed, they are said to exert forces on each other. The measure of this force is the product of mass times acceleration. The newton N is that force which gives to a mass of one kilogram, 1 kg, an acceleration of one metre per second squared, 1 m/s^2.

ceived by Newton is stated clearly in his second principle (Ref. 6):

> " The acceleration of a particle (body) is directly proportional to the resultant external force acting on the particle, is inversely proportional to the mass of the particle, and has the same direction as the resultant force."

This relationship can be written:

$$a = \frac{kF}{m}* \tag{4-23}$$

where

a = acceleration
k = numerical constant
F = force
m = mass

Usually, this equation is written in the form,

$$kF = ma \tag{4-24}$$

Weight is force; weight is not mass. Objects with mass fall toward the earth. The force required to keep them from falling toward the earth is called their weight. A table is said to exert an upward force on an object equal to the weight of the object. The same object experiences a downward force, equal to its weight, which is called a gravitational force.

Gravitational forces are said to exist between all bodies having mass and these forces are directed such that the bodies fall (are accelerated) toward each other. Gravitational forces between bodies are dependent upon separation between the bodies. The magnitude of this attractive force is inversely proportional to their separation squared.

Weight is that gravitational force exerted on a body specifically by the earth or, more generally, planets and large satellites such as the moon. Weight is not constant over the surface of the earth; at higher altitudes weight, the force of gravity, is less than it is at sea level. The measured weight of a body varies by slightly more than 0.5% at different locations on the earth. The mass of a body does not vary with location; it is a constant.

Mass and weight are related by the practice of saying that the observed gravitational effect is equivalent to an acceleration. Thus an acceleration of gravity g can be defined, measured, and substituted for a in Eq. 4-24 to obtain the relationship between mass and weight:

$$kW = mg \tag{4-25}$$

Based upon the concepts introduced here and particularly the quantitative relationships between mass, force, and weight (Eqs. 4-24 and 4-25), different systems of mechanical units are considered in par. 4-3.2 with the objective of eliminating the confusing that frequently surrounds the mechanical units that have been and are in use.

4-3.2 SYSTEMS OF MECHANICAL UNITS

The systems of mechanical units to be considered are given in Table 4-2. These units are listed in the following systems:

1. The absolute systems:
   a. International System of Units (SI)
   b. Metre-Kilogram-Second (MKS)
   c. Centimetre-Gram-Second (CGS)
   d. Foot-Pound-Second (FPS)
2. The gravitational systems:
   a. British Type I ("foot-slug-second")
   b. British Type II ["foot-(pound-mass)-second"]
   c. Metric Type II ["metre-(kilogram-mass)-second"]

*This is, in general, a vector equation with the variables a and F being vectors. It is sufficient, for the purpose here, to consider one-dimensional situations.

TABLE 4-2
SYSTEMS OF MECHANICAL UNITS (Refs. 6, 7)

	Absolute Systems				Gravitation Systems		
	SI	MKS	CGS	FPS	British Type I	British Type II	Metric Type II
Newton's second principle	$F = ma$	$F = ma$	$F = ma$	$F = ma$	$F = ma$	$g_o F = ma$ [a]	$g_o F = ma$ [b]
Length	metre (m)	metre (m)	centimetre (cm)	foot (ft)	foot (ft)	foot (ft)	metre (m)
Mass	kilogram (kg)	kilogram (kg)	gram (g)	pound (lb) [c]	slug	pound-mass (lbm)	kilogram-mass (kgm)
Time	second (s)	second (sec)	second (sec)	second (sec)	second (sec)	second (sec)	second (sec)
Force	newton (N)	newton (nt)	dyne	poundal (pdl)	pound (lb) [d]	pound-force (lbf)	kilogram-force (kgf)
Velocity	m/s	m/sec	cm/sec	ft/sec	ft/sec	ft/sec	m/sec
Acceleration	m/s^2	m/sec^2	cm/sec^2	ft/sec^2	ft/sec^2	ft/sec^2	m/sec^2
Torque	N • m	nt • m	dyne • cm	pdl • ft	lb • ft	lbf • ft	kgf • m
Moment of Inertia	kg • m^2	kg • m^2	g • cm^2	lb • ft^2	slug • ft^2	lbm • ft^2	kgm • m^2
Pressure	N/m^2, pascal (Pa)	nt/m^2	$dyne/cm^2$	pdl/ft^2	lb/ft^2	lbf/ft^2	kgf/m^2
Energy	N • m, joule (J)	nt • m, joule	dyne • cm erg	ft • pdl	ft • lb	ft • lbf	m • kgf
Power	N • m/s J/s watt (W)	watt	erg/sec	ft • pdl/sec	ft • lb/sec	ft • lbf/sec	m • kgf/sec
Momentum	kg • m/s,	kg • m/sec	g • cm/sec	lb • ft/sec	slug • ft/sec	lbm • ft/sec	kgm • m/sec
Impulse	N • s	nt • sec	dyne • sec	pdl • sec	lb • sec	lbf • sec	kgf • sec

[a] $g_o = 32.173\ 98$

[b] $g_o = 9.806\ 65$

[c] Sometimes referred to as pound-mass (1 pound = 1 pound-mass; see Table 4-3)

[d] Sometimes referred to as pound-force (1 pound = 1 pound-force; see Table 4-4)

For each system in Table 4-2, the base mechanical units for length, time, and mass or force and a number of important derived mechanical units are given. Conversion of these base and derived units is considered in par. 4-3.3.

In all the systems of mechanical systems considered here, time and space are taken as independent quantities and units for these two dimensions are defined on the basis of convenience. In all cases the unit of time is the second. The units for space (length) are as given in Table 4-2 and are the centimetre, foot, or metre.

Units for space and time having been selected, units for mass and force are selected for convenience with respect to both unit magnitude and their relationship in Eq. 4-24. Defining the units for mass and force independently of Eq. 4-24 means that k in that equation will be determined by the sizes of those units. In that case k would be a fixed constant with no physical significance. What has actually been done in developing the systems of units in Table 4-2 is to choose a convenient unit of either mass (or force) and then to use Eq. 4-24 as the defining equation for the quantity, force (or mass), with k set to some convenient value. In those systems, such as the SI, called *absolute* systems k is set at the value one in this process. In the SI, the unit of mass is defined first as a base unit, and force is a derived unit using Eq. 4-24. Thus one newton is the force required to accelerate a mass of one kilogram at a rate of one metre per second per second. Note that the strength of the gravitational effect on earth is not involved in the definitions of units in these absolute systems.

In the gravitational systems of units, the earth's gravitational effect is a factor in the definition of the units of force or of mass. Specifically, the standard value of the acceleration of gravity g_o on the earth's surface (at sea-level) enters into these definitions. The standard values for g_o are:

$$g_o = 9.806\,65 \text{ m/s}^2$$

and

$$g_o = 32.173\,980 \text{ ft/s}^2$$

There are two types of gravitational systems of units. The "Type II" gravitational systems, British Type II and Metric Type II are considered first. In these two systems, the base units for mass — the pound-mass and kilogram-mass — are related to SI units as follows:

$$\text{one pound-mass} = 0.453\,592\,427\,7 \text{ kg}$$

and

$$\text{one kilogram-mass} = 1 \text{ kg}$$

As indicated in Table 4-2, Newton's second principle — applicable when Type II systems of units are used — is obtained from Eq. 4-24 by setting k equal to g_o

$$g_o F = ma \tag{4-26}$$

This equation defines the units of force in these systems of units by rewriting it in the form:

$$F = \left(\frac{a}{g_o}\right)m \tag{4-27}$$

Thus, the unit of force is that force which will accelerate one unit of mass at a rate equal to the standard acceleration of gravity g_o. This is the difference between the gravitational Type II systems and both the gravitational Type I and the absolute systems of units. In the latter systems of units, one unit of force is defined as that force which will impart to one unit of mass an acceleration equal to one unit of acceleration. Note also that at sea level the weight of an object is numerically equal to its mass when Type II systems of units are used. Thus a mass of one kilogram-mass (one pound-mass) weighs one kilogram-force (one pound-force) at sea level. In all other systems of units, one unit of mass weighs g_o (with appropriate units) at sea level. Finally, it should be noted that one kilogram-mass is equal to one kilogram and that one pound-mass is equal to one pound in the foot-pound-second system.

In the British Type I system of units, the gravitation force unit is selected and the mass unit is defined in terms of that force unit by Newton's second principle. Specifically, the force unit, the pound, is the force of gravity at sea level on one pound-mass (i.e., the mass unit in the British Type II system). Thus, one pound in the British Type I system is equal to one pound-force in the British Type II system. The mass unit is the

slug; it is the mass to which a force of one pound will impart an acceleration of one foot per second per second. Note that the British Type I system is referrred to as a gravitational system of units because the unit of force is defined as the force due to gravity at sea level on a specific mass as is the case with the Type II systems. However, the mass unit — slug — is related numerically to the force unit in the same manner as in the absolute systems of units.

Conversion factors (in the form of unit equalities) for converting all force and mass units considered here to SI units are given in Table 5-1. For convenience, factors for converting any of these mass and force units to any other mass and force units are given in Table 4-3 and Table 4-4, respectively (Refs. 3,6).

In summary, it should be noted that the mass unit for the Metric Type II system, kilogram-mass, is equivalent to the SI mass unit, kilogram. The mass unit in the British Type II system, pound-mass, is equal to the foot-pound-second mass unit (FPS), pound. In the case of force units, the force unit in the British Type II system, pound-force, is equal to the force unit in the British Type I system, pound.

Examples of and methods of converting mechanical units are presented in par. 4-4 on the conversion of derived units.

4-4 CONVERSION OF THE UNITS OF DERIVED QUANTITIES

The conversion of the units of derived quantities proceeds generally in the same manner as the conversion of base units and the units of single quantities as presented in par. 4-1. The conversion is performed by forming unit conversion factors for each separate unit in the units of a derived quantity; performing the indicated calculations; and rounding off the result to the appropriate number of significant digits. These steps are demonstrated in the following examples:

Example No. 5: Convert 10.3×10^4 ft • lb to newton-metres.

a. With force expressed in pounds, we know the original units are British Type I.

b. Three significant digits are indicated and are reasonable.

c. For converting feet to metres, the unit equality is obtained from Table 5-1 and the unit conversion factor is formed in the following manner:

$$1 \text{ ft} = 3.048 \times 10^{-1} \text{ m}$$

$$1 = \frac{3.048 \times 10^{-1} \text{ m}}{\text{ft}}$$

d. For converting pounds to newtons, the unit equality is obtained from Table 5-1 or Table 4-4 and the unit conversion factor is formed in the following manner:

$$1 \text{ lb} = 4.448\,222 \text{ N}$$

$$1 = \frac{4.448\,222 \text{ N}}{\text{lb}}$$

e. The conversion is accomplished by multiplying the original quantity by the unit conversion factors:

$$10.3 \times 10^4 \text{ ft} \bullet \text{lb} \times \frac{3.048 \times 10^{-1} \text{ m}}{\text{ft}} \times \frac{4.448\,222 \text{ N}}{\text{lb}}$$

$$= 10.3 \times 10^4 \times 3.048 \times 10^{-1} \times 4.448\,222 \frac{\text{ft} \bullet \text{lb} \bullet \text{m} \bullet \text{N}}{\text{ft} \bullet \text{lb}}$$

Performing the calculation and "cancelling the units" ft and lb give:

$$1.396\,492\,608 \times 10^5 \text{ N} \bullet \text{m}$$

f. From the rule, par. 4-2.3, for significant digits in products and quotients, the result can have no more significant digits than is in the number with the smallest number of significant digits entering the calculation. Thus the result is rounded to three significant digits:

$$1.40 \times 10^5 \text{ N} \bullet \text{m}$$

TABLE 4-3
UNIT CONVERSION MATRIX—MASS

	SI and MKS kilogram*	CGS gram	FPS pound	British Type I slug	British Type II pound-mass	Metric Type II kilogram-mass
SI and MKS kilogram =	1	10^3	2.204 622	$6.852\ 177 \times 10^{-2}$	2.204 622	1
CGS gram =	10^3	1	$2.204\ 622 \times 10^{-3}$	6.852×10^{-5}	$2.204\ 622 \times 10^{-3}$	10^{-3}
FPS pound* =	0.453 592	453.592	1	3.108×10^{-2}	1	0.453 592
British Type I slug =	14.593 903	$1.459\ 390 \times 10^4$	32.173 980	1	32.173 980	14.593 903
British Type II pound-mass =	0.453 592	453.592	1	3.108×10^{-2}	1	0.453 592
Metric Type II kilogram-mass =	1	10^3	2.204 622	$6.852\ 177 \times 10^{-2}$	2.204 622	1

*Example: Convert X pounds to kilograms (SI). Form equation:

1 lb = 0.453 592 kg. Form unit factor, $1 = \frac{0.453\ 592}{\text{lb}}$ kg.

Multiply X pounds by unit factor. Round off appropriately.

The other approach to selecting the number of significant digits is to convert a unit in the position of the last significant digit in the original quantity:

$$0.1 \times 10^4 \text{ ft} \bullet \text{lb} \times \frac{3.048 \times 10^{-1} \text{ m}}{\text{ft}} \times \frac{4.448\,222 \text{ N}}{\text{lb}} = 0.013\,581 \times 10^5 \text{ N} \bullet \text{m}$$

Thus, rounding off to the one-hundredth position in the result implies slightly better accuracy than the original quantity.

Example No. 6: Convert surface tension of 1.68×10^{-6} poundals per ft (pdl/ft) to newtons per metre.

a. The conversion is from foot-pound-second (FPS) units to SI units.

b. Assume the three digits in the original quantity are significant.

c. For converting poundals to newtons, the unit equality is obtained from Table 5-1 or Table 4-4 and the unit conversion factor is formed in the following manner:

$$1 \text{ pdl} = 1.382\,550 \times 10^{-1} \text{ N}$$

$$1 = \frac{1.382\,550 \times 10^{-1} \text{ N}}{\text{pdl}}$$

d. For converting feet to metres, the unit equality is obtained from Table 5-1:

$$1 \text{ ft} = 3.048 \times 10^{-1} \text{ m}$$

Note that since ft occurs in the denominator of the original quantity, the unit conversion factor must have ft in the numerator in order to remove ft from the units of the original quantity. Thus the conversion factor in this case is:

$$1 = \frac{1 \text{ ft}}{3.048 \times 10^{-1} \text{ m}}$$

e. The conversion is accomplished by multiplying the original quantity by the two unit factors:

$$1.68 \times 10^{-5} \frac{\text{pdl}}{\text{ft}} \times \frac{1.382\,550 \times 10^{-1} \text{ N}}{\text{pdl}} \times \frac{1 \text{ ft}}{3.048 \times 10^{-1} \text{ m}}$$

$$= \frac{1.68 \times 10^{-5} \times 1.382\,550 \times 10^{-1}}{3.048 \times 10^{-1}} \times \frac{\text{pdl} \bullet \text{N} \bullet \text{ft}}{\text{ft} \bullet \text{pdl} \bullet \text{m}} = 7.620\,354\,330 \times 10^{-6} \text{ N/m}$$

f. The original quantity has the fewest (three) significant digits involved in this calculation. Thus the result should contain no more than three significant digits:

$$7.62 \times 10^{-6} \text{ N/m}$$

Example No. 7: Convert a pressure of 12.389 dyn/cm^2 to pascals.

a. The conversion is from CGS units to SI units. The pascal is a unit of pressure equal to one N/m^2. Thus, 12.389 dyn/cm^2 is converted to N/m^2 and then Pa is substitute for N/m^2.

b. Five significant digits is not unreasonable for a very precise pressure measurement.

c. For converting dynes to newtons the units equality is obtained from Table 5-1 or Table 4-4:

$$1 \text{ dyn} = 1 \times 10^{-5} \text{ N}$$

$$1 = \frac{1 \times 10^{-5} \text{ N}}{\text{dyn}}$$

d. The relationship between metre and centimetre is (from Table 2-4):

$$1 \text{ cm} = 10^{-2} \text{ m}$$

TABLE 4-4
UNIT CONVERSION MATRIX—FORCE

	SI and MKS newton	CGS dyne	FPS poundal*	British Type I pound	British Type II pound-force	Metric Type II kilogram-force
SI and MKS newton =	1	10^5	7.233	0.2248	0.2248	0.1020
CGS dyne =	10^{-5}	1	7.233×10^{-5}	2.248×10^{-6}	2.248×10^{-6}	1.020×10^{-6}
FPS poundal* =	0.138 2550	$1.382\ 550 \times 10^4$	1	3.108×10^{-2}	3.108×10^{-2}	1.410×10^{-2}
British Type I pound =	4.448 222	$4.448\ 222 \times 10^5$	32.173 980	1	1	0.453 592
British Type II pound-force =	4.448 222	$4.448\ 222 \times 10^5$	32.173 980	1	1	0.453.592
Metric Type II kilogram-force =	9.807	9.807×10^5	70.93	2.205	2.205	1

*Example: Convert X dynes to poundals. Form equation: 1 dyn = 7.233×10^{-5} pdl. Form unit factor, $1 = \dfrac{7.233 \times 10^{-5}\ \text{pdl}}{\text{dyn}}$. Multiply X dyn by unit factor. Round off appropriately.

Noting that cm is in the denominator of the original quantity, the unit conversion factor is formed in the following manner:

$$1 = \frac{1\ \text{cm}}{10^{-2}\ \text{m}}$$

e. The conversion is accomplished by multiplying by the first unit conversion factor and (since cm in the original is squared) by the second unit factor squared:

$$12.389\frac{\text{dyn}^2}{\text{cm}^2}\times\frac{10^{-5}\ \text{N}}{\text{dyn}}\times\left[\frac{1\ \text{cm}}{10^{-2}\ \text{m}}\right]^2 = \frac{12.389\times10^{-5}}{(10^{-2})^2}\times\frac{\text{dyn}\bullet\text{N}\bullet\text{cm}^2}{\text{cm}^2\bullet\text{dyn}\bullet\text{m}^2} = 1.2389\ \text{N/m}^2$$

f. It can be assumed that when a unit equality is an exact relationship as is the case in converting centimetres to metres and dynes to newtons, that there are an infinite number of significant digits in the numerical factors (i.e., 10^{-2} and 10^{-5}). Thus, the original quantity has the least number (five) of significant digits in this example and the result also should have five significant digits:

$$1.2389\ \text{N/m}^2$$

Example No. 8: Convert 12.389 dyn/cm^2 to pascals.

a. This is the same as the previous example. The conversion is made in a more straightforward manner.

b. From Table 5-1:

$$1\ \text{dyn/cm}^2 = 1\times10^{-1}\ \text{Pa}$$

$$1 = \frac{10^{-1}\ \text{Pa}}{\text{dyn/cm}^2}$$

c. Convert as follows:

$$12.389\ \text{dyn/cm}^2\times\frac{10^{-1}\ \text{Pa}}{\text{dyn/cm}^2} = 1.2389\ \text{Pa}$$

4-5 CONVERSION OF TEMPERATURE UNITS

Two kinds of temperature unit conversions are encountered: (1) conversion of the units of temperatures; and, (2) conversion of the units of temperature intervals and differences. Conversions between thermodynamic temperature (kelvin, K), Celsius temperature (degree Celsius, °C), and Fahrenheit temperature (degree Fahrenheit, °F) are considered here.

The equations for converting temperature units are given in Fig. 4-1. Conversion of temperature units using these relationships are presented in the following examples:

Example No. 9: Convert 31.2°C to kelvins.

a. Three significant digits express this temperature in °C accurate to the nearest one-tenth °C. This is a fairly precise measured value of temperature.

b. From Fig. 4-1, the relationship between °C and kelvins is:

$$T(\text{K}) = t(°\text{C}) + 273.15$$

where T(K) is thermodynamic temperature in kelvins (K) and t(°C) is Celsius temperature in °C.

c. Substituting 31.2 for t:

$$T = (31.2 + 273.15)\ \text{K}$$

$$T = 304.35\ \text{K}$$

d. Since one kelvin and one degree Celsius are by definition the same temperature increment, a measurement to the nearest one-tenth degree Celsius is equivalent to a measurement to the nearest one-tenth kelvin. Thus, the correct result is:

$$T = 304.4\ \text{K}$$

Note that there are four significant digits in the result and only three significant digits in the original quantity. This is consistent with the rules for rounding off in addition and subtraction given in par. 4-2.3.

Example No. 10: Convert a temperature difference Δt_F of 39.06°F to a temperature difference in kelvins and degrees Celsius.

a. From Fig. 4-1:

$$t_F = 1.8\,T - 459.67$$

where t_F is Fahrenheit temperature (°F) and T is thermodynamic temperature (K).

b. Since we are dealing with a temperature difference (or interval), this quantity can be written $t_{F1} - t_{F2}$. The conversion is to the difference $T_1 - T_2$. Substituting t_{F1} and T_1 into the above equation gives:

$$t_{F1} = 1.8\,T_2 - 459.67$$

Substituting t_{F2} and T_2 gives:

$$t_{F2} = 1.8\,T_2 - 459.67$$

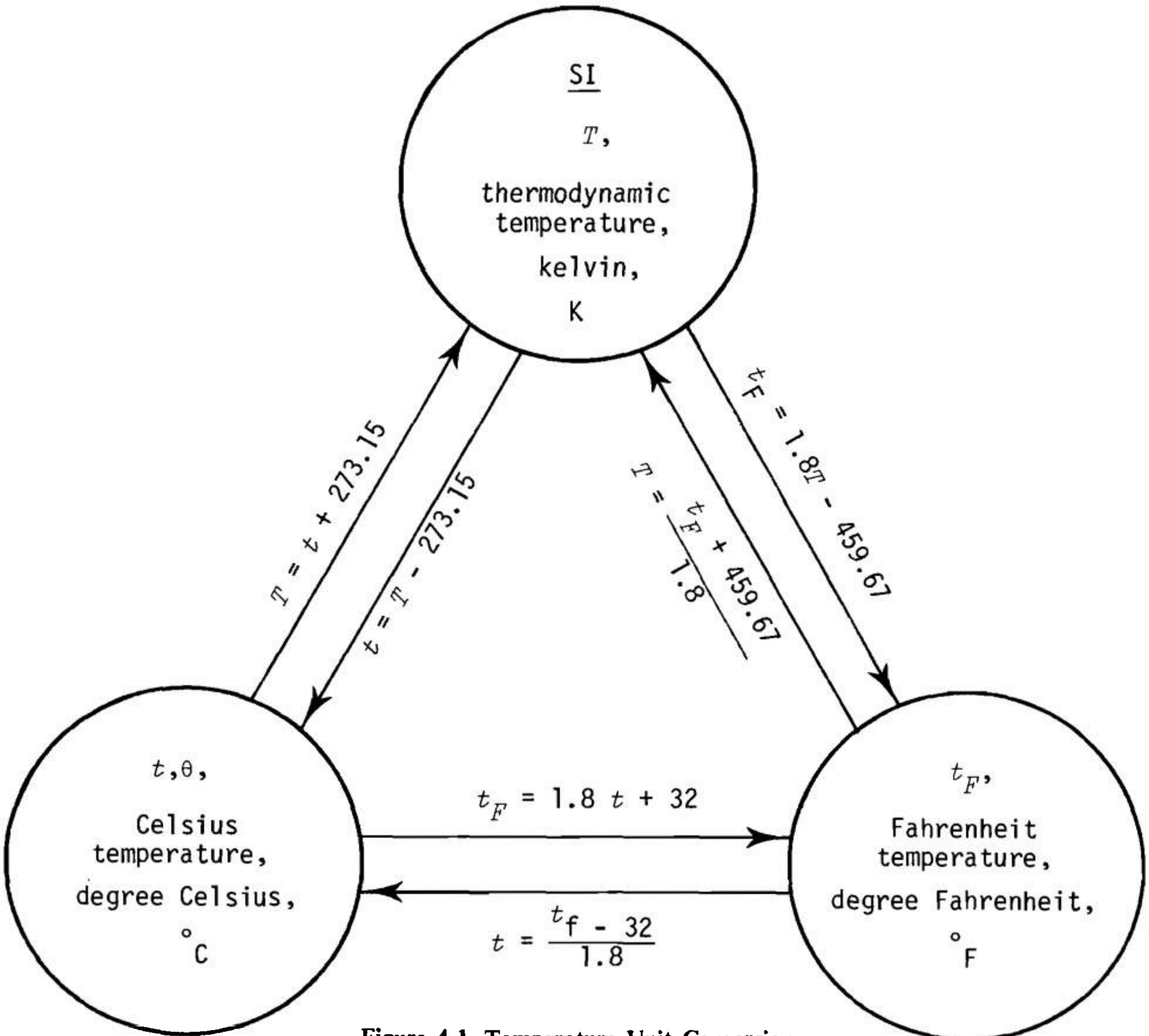

Figure 4-1. Temperature Unit Conversions

Subtracting the second of these equations from the first gives:

$$t_{F1} - t_{F2} = 1.8\,(T_1 - T_2)$$

or

$$\Delta T = (1/1.8)\,\Delta t_F$$

c. Substituting 39.06 °F for Δt_F gives:

$$\Delta T = (1/1.8)\,39.06 = 21.700\,000 \text{ K*}$$

d. One unit in the position of the least significant digit in the original quantity is 0.01 °F. Converting this temperature *interval* to kelvins gives:

$$\delta T = (1/1.8) \times 0.01 = 0.0056 \text{ K}$$

This is smaller than 0.01 K and larger than 0.001 K therefore the converted value should be rounded to:

$$\Delta T = 21.700 \text{ K}$$

e. A temperature interval in kelvins is numerically equal to the same temperature interval in degrees Celsius. Thus:

$$\Delta T^{**} = 21.700 \text{ K} = 21.700 \text{ °C}$$

Example No. 11: Convert 207°F to kelvins.

a. This temperature is assumed to be accurate to the nearest degree.

b. From Fig. 4-1, the relationship between °F and K is:

$$T(\text{K}) = \frac{t_F(\text{°F}) + 459.67}{1.8}$$

where T(K) is thermodynamic temperature in kelvin (K) and t_F(°F) is Fahrenheit temperature in degrees Fahrenheit (°F).

c. Substituting 207 for t_F in this equation gives:

$$T = \left(\frac{207 + 459.67}{1.8}\right) \text{K}$$

$$T = 370.37 \text{ K}$$

d. Note that a temperature interval of one degree Fahrenheit is equivalent to (1/1.8) kelvin (or 0.556 kelvin). Thus, with the original temperature being accurate to one degree Fahrenheit, the converted value should be rounded to the nearest tenth of a kelvin. This gives:

$$T = 370.4 \text{ K}$$

e. It is also reasonable to conclude that the result should be rounded to the nearest one-half kelvin and written:

$$T = 340.5 \pm 0.5 \text{ K}$$

4-6 ELECTROMAGNETIC UNITS

In the general area of electromagnetics one may and is likely to encounter three systems of units in addition to the SI. These are (Ref. 6):

1. Electrostatic (ESU)
2. Electromagnetic (EMU)
3. Practical (MKS).

---

*Not surprising since we already know this relationship from Eq. 3-3.

**Some notation (Δ) indicating temperature interval must be used!

The latter system (MKS) in its rationalized form has evolved to the SI. The major differences between rationalized MKS (RMKS) and the SI are unit name and symbols. Both ESU and EMU incorporate the CGS base units; i.e., the centimetre, gram, and second. Quantities and units in these systems are given in Table 4-5.

The force between two charges can be written (Ref. 8):

$$F = \frac{1}{\epsilon}\left(\frac{Q_1 Q_2}{d^2}\right) \tag{4-28}$$

where

Q_1, Q_2 = electric charges
d = separation between charges
F = force
ϵ = permittivity

With all quantities set to unit value, this equation defines charge in the ESU in terms of unit force (dyne), unit separation (centimetre), and unit permittivity (ϵ) of free space. The units of the ESU are based on the CGS mechanical units and the unit of charge, the statcoulomb which is defined by Eq. 4-28. The ESU units are given the prefix stat- to distinguish them; e.g., statvolt, statampere, etc.

The force between two magnetic poles is:

$$F = \frac{1}{\mu}\left(\frac{m_1 m_2}{d^2}\right) \tag{4-29}$$

where

m_1, m_2 = magnetic pole strength
d = separation
F = force
μ = permeability

With unit force (dyne), unit separation (centimetre), unit permeability (μ) of free space, and m_1 and m_2 equal to unit magnetic pole strength (abampere centimetre), Eq. 4-29 defines the unit of magnetic field strength. The EMU is based on the CGS base units and the unit of magnetic pole strength defined by Eq. 4-29 (Ref. 8). Units of the EMU are distinguished by the prefix ab-; e.g., abampere.

The ESU and the EMU were developed for scientific work in electrostatics and electromagnetics, respectively. The sizes of the units in these systems are not convenient; e.g., one abfarad equals 1×10^9 farads, one abvolt equals 1×10^{-8} volt, one statohm equals 8.987×10^{11} ohms, etc. When using the ESU and EMU, it is necessary that one be very familiar with the conversion of units between these systems.

The MKS electromagnetic system evolved or was developed in order to give a single system with units of practical sizes which can be used conveniently in all areas of research and engineering involving electrical, magnetic, and electromagnetic phenomena. The rationalized MKS (RMKS) system incorporates definitions of permeability and permittivity which result in the factors $1/(2\pi)$ and $1/(4\pi)$ appearing in the equations describing electric and magnetic phenomena having cylindrical and spherical symmetry, respectively. (This is discussed briefly in par. 4-7 (Ref. 6).)

Table 4-5 is included in order to assist in the identification of equivalent units in the SI, MKS, ESU, and EMU. Conversion factors for many of the units in Table 4-5 are given in Tables 5-1 and 5-2. In those cases for which conversion factors are not given, the methods in par. 4-4 for the conversion of derived quantities should be used. Par. 4-7, which is concerned with equations and formulas, is relevant to the conversion of electromagnetic units, particularly when going from EMU or ESU to the RMKS or SI.

4-7 EQUATIONS

During the transition to a much broader use of the SI; scientists, engineers, and technicians frequently may be faced with the necessity of using equations and formulas developed for use in any one of a number of systems of units other than the SI. In general this will involve one of two situations: (1) the equation or

TABLE 4-5
ELECTRICAL AND MAGNETIC UNITS

Quantities/ Formulas	SI	MKS	EMU	ESU
Length	metre (m)	metre (m)	centimetre (cm)	centimetre (cm)
Mass M	kilogram (kg)	kilogram (kg)	gram (g)	gram (g)
Time t	second (s)	second (sec)	second (sec)	second (sec)
Force F	newton (N) = kg • m/s^2	newton (nt) kg • m/sec^2	dyne = g • cm/sec^2	dyne = g • cm/sec^2
Energy W	joule (J) = m • N	joule = m • nt	erg = cm • dyn	erg = cm • dyn
Power P	watt (W) = J/s	watt = joule/sec	erg/sec	erg/sec
Charge Q	coulomb (C)	coulomb (coul)	abcoulomb (abcoul)	statcoulomb (statcoul)
Current $I = Q/t$	ampere (A)	ampere (amp) = coul/sec	abampere (abamp) = abcoul/sec	statampere (statamp) = statcoul/sec
Electric potential $V = W/Q$	volt (V)	volt (v) joule/coul	abvolt (abv) = erg/abcoul	statvolt (statv) = erg/statcoul
Resistance $R = V/I$	ohm (Ω)	ohm = joule • sec/$coul^2$	abohm = erg • sec/$abcoul^2$	staohm = erg • sec/$statcoul^2$
Electric intensity $E = V/L = F/Q$	V/m = N/C	volt/metre = nt/coul	abvolt/cm = dyne/abcoul	statvolt/cm = dyne/statcoul
Capacitance $C = Q/V$	farad (F) = C/V = C^2J	farad = coul/v = $coul^2$/joule	abfarad (abf) = abcoul/abv	statfarad (statf) = statcoul/statv
Dielectric displacement	C/m^2	coul/m^2	1 EMU = (1/4π) abcoul/cm^2	1 ESU = (1/4π) x statcoul/cm^2

TABLE 4-5 (Cont'd)

Quantities/ Formulas	SI	MKS	EMU	ESU
Electric inductive capacity $e_e = D/E$	F/m = C/J • m	farad/m = $coul^2$/joule • m	1 EMU = (1/4π) x $abcoul^2$/erg • cm	1 ESU = (1/4π) x $statcoul^2$/erg • cm
Magnetic flux $\Phi = B$ x area	weber (Wb)	weber = joule/amp	maxwell = erg/abamp	1 ESU = erg/statamp
Magnetic flux density $B = F/LI$	tesla (T) = Wb/m^2	weber/m^2 = nt/amp • m	gauss = dyne/abamp • cm	1 ESU = dyne/statamp • cm
Magnetic moment $m = I$ x area	A • m^2	amp • m^2	abamp • cm^2	statamp • cm^2
Magnetization $M = m$/volume	A/m	amp/m	abamp/cm	statamp/cm
Magnetizing force H	AT/m	amp-turn/m	oersted = (1/4π) x abamp-turn/cm	1 ESU = (1/4π) x statamp-turn cm
Magnetomotive force $MMF = HL$	AT	amp-turn	gilbert = (1/4π) x abamp-turn	1 ESU = (1/4π) x statamp-turn
Reluctance $R = MMF/\Phi$	AT • W = A^2/J	amp-turn weber = amp^2/joule	gilbert/maxwell = (1/4π) $abamp^2$/erg	1 ESU = (1/4π) x $statamp^2$/erg
Inductance $L = V/dI/dT$	henry (H) = Ω • s = J/A^2	henry = ohm • sec = joule/amp^2	abhenry = abohm abohm • sec = erg/$abamp^2$	stathenry = statohm • sec = erg/$statamp^2$
Magnetic inductive capacity $e_m = B/H$	H/m = N/A^2	henry/m = nt/amp^2	gauss/oersted = 4π abhenry/cm = 4π dyne/$abamp^2$	1 ESU = 4π stathenry/cm 4π dyne/$statamp^2$
Permittivity ε_o	8.854 185 3 x 10^{-12} F/m or 1/(36π x 10^9) F/m	8.854 185 3 x 10^{-12} F/m or 1/36 π x 10^9 F/m	$(1/c^2)$ abfarad/cm or 1.112 649 7 x 10^{-21} abfarad/cm	1 statfarad/cm
Permeability μ_o	4π x 10^{-7} H/m or 1.256 637 062 x 10^{-6} H/m	4π x 10^{-7} H/m or 1.256 637 062 x 10^{-6} H/m	1 abhenry/cm	$(1/c^2)$ stathenry/cm or 1.112 649 7 x 10^{-21} stathenry/cm

formula and the data which will be substituted into the equation or formula have non-SI units and they are compatible; (2) the equation or formula and the data are not compatible. In the first case, it may be decided that calculations should be made in the non-SI system of units and, if desirable, the results converted to SI units. For example, a formula for calculating range in thousands of yards for a projectile based on initial velocity in feet per second and elevation angle in degrees may be involved. If all input data are available in feet per second and degrees, it is probably not effective to modify the formula and convert the input data to SI units. It may not even be desirable to convert the results to SI units.

It is the second situation where some modification of an equation or formula is necessary or desirable that is of concern here. Suppose that one is working with one or more equations developed in the feet per second (FPS) or some other system of units and that the data to be substituted into these equations must be expressed in SI units. The problem to be addressed here is that of modifying the equation(s) such that it can be used with quantities expressed in SI units. Before considering specific cases and how to handle them, an important characteristic of equations and of the units in equations is presented in par. 4-7.1.

Dimensional analysis is treated rigorously and thoroughly in a number of texts (Refs. 1, 2, 11, and 12). The approach taken here is not rigorous. The intent is to present a method of identifying hidden units and modifying the numerical constants in an equation such that the equation can be used with SI units.

4-7.1 DIMENSIONAL ANALYSIS OF EQUATIONS

In the presentation the notation $\{X\}$ will mean "the units of" the quantity X where X in general will have a numerical value and units. Examples of X are in force F, length L, and mass M. Examples of "the units of" X are:

$\{F\}$ = n, lbf, dyn

$\{V\}$ = m/s, in./min, mi/hr

$\{Q\}$ = C, abcoul, statcoul

$\{L\}$ = m, km, cm, yd

$\{\text{energy}\}$ = J, in. • lbf, erg, m^2 • kg/s^2.

Note that $\{V\}$ means the unit or units of speed in a specific situation; the unit(s) may be part of any system of units and may be expressed in any form that is legitimate. Assume that a quantity V is expressed in foot-pound-second units; then, $\{V\}$ = ft/sec. After conversion of the quantity V to SI units, $\{V\}$ = m/s.

The most important dimensional property of an equation or formula is that it can be written in a form such that the units of and the numerical value of the left-hand side of the equation are equal to the units of and the numerical value of the right-hand side of the equation. These equalities may not be obvious in any specific case for one or both of the following two reasons: (1) if units from two or more systems of units are used for different quantities in an equation, numerical factors of proportionality are introduced; and (2) there may be one or more "hidden dimensions and units" associated with numerical factors (including the factor one) in the equation.

As a simple example consider the unit equality (from Table 5-1):

$$1 \text{ in.} = 0.0254 \text{ m} \tag{4-30}$$

Neither the units nor the numerical values of left-hand and right-hand sides is equal. The physical quantities (specific lengths) represented in the equation are equal. The factor of proportionality 0.0254 appears because two systems of units (FPS and SI) are used; this is the reason the equation is useful. But, it must be possible to write Eq. 4-30 so that the numerical values and units of each side of the equality are equal. If, in the equality, the unit inch is converted to metres, the equation becomes:

$$0.0254 \text{ m} = 0.0254 \text{ m} \tag{4-31}$$

If the unit metre is converted to inches, the equation is:

$$1 \text{ in.} = 1 \text{ in.} \tag{4-32}$$

If this were not true, then Eq. 4-30 would not be a valid equality.

It should be noted that in the original equality (Eq. 4-30) both numerical value and units were different. The statement that an equation can be written such that both numerical value and units are equal can be extended to the following: (1) if either the units or the numerical values of the two sides of a valid equation are equal, then both the units and numerical values are equal; and (2) if either are not equal, then both are not equal. Generally, we are concerned only with the former situation where units and numerical values are equal. It is only in the case of identities and equalities such as Eq. 4-30 that the latter are useful.

Eq. 4-33 gives an approximate value of the low-frequency inductance L of a single-layer solenoid (Ref. 9).

$$L = F\, n^2 d,\ \mu\text{H} \tag{4-33}$$

where

L = inductance
n = number of turns in the solenoid, dimensionless
d = coil diameter
F = form-factor depending on the ratio of coil diameter to coil length and is evaluated using an empirically determined graph

For a specific example, F has the value 0.0173 when the ratio, diameter to length, is unity (Ref. 9). This gives:

$$L = 0.0173\, n^2 d \tag{4-34}$$

The explicit units of the two sides of Eq. 4-34 obviously are not the same. Note that n is a number having no units. The "hidden dimensions or units" of the factor 0.0173 must be determined. Use is made of the following: Calculating inductance for a specific value of d is accomplished by forcing the numerical values of the two sides of the equation to be equal; if the numerical values are equal, then the units must also be equal. Eq. 4-34 is divided by n^2d to obtain:

$$\frac{L}{n^2 d} = 0.0173 \tag{4-35}$$

Thus, the units of the form-factor, 0.0173, are:

$$\{0.0173\} = \frac{\{L\}}{\{d\}} = \frac{\mu\text{H}}{\text{in.}} \tag{4-36}$$

Therefore, Eq. 4-34 can be written

$$L\ \mu\text{H} = [0.0173\ (\mu\text{H/in.})]\ n^2 d\ \text{in.} \tag{4-37}$$

or, cancelling inches:

$$L\ \mu\text{H} = 0.0173\, n^2 d\ \mu\text{H} \tag{4-38}$$

This demonstrates that the factor 0.0173 (or 0.0173 n^2) has the hidden units microhenries per inch and that the units of both sides of the equation are explicitly the same.

By working with the principle that the units *and* numerical values of both sides of an equation are the same, an equation developed for use in one system of units can be modified (if necessary) for use with another system of units. Examples are given in par. 4-7.2.

4-7.2 MODIFICATION OF EQUATIONS FOR USE IN THE SI

The first step in using a "non-SI" equation with quantities expressed in SI units is to determine if the equation must be modified in any way. Consider the relationship between force, mass, and acceleration in the FPS system. From Table 4-2:

$$F = ma \tag{4-39}$$

where F is force in poundals, m is mass in pounds, and a is acceleration in feet/second^2. Putting these units in Eq. 4-39 gives:

$$F\ \text{pdl} = m\ \text{lb} \times a\ \text{ft/s}^2 \tag{4-40}$$

From the definition of the force unit (see par. 4-3.2) in the FPS system, the poundal is that force which gives a mass of one pound an acceleration of one foot/second². Thus,

$$1 \text{ pdl} = 1 \text{ lb} \cdot 1 \text{ ft/s}^2 \tag{4-41}$$

The unit pdl is equal to the unit lb • ft/s²; and there are no hidden units. The same is true in the other absolute systems of units and the British Type I system provided the units of a single system of units are used without prefixes (kg is an exception); Eq. 4-39 is valid. Thus, Eq. 4-39 can be used with any consistent set of units listed in Table 4-6.

TABLE 4-6
COMBINATIONS OF UNITS THAT CAN BE USED
IN THE EQUATION $F = ma$

Force	Mass	Acceleration
newton	kilogram	metre per second²
dyne	gram	cm per second²
poundal	pound	foot per second²
pound	slug	foot per second²

Note that units of the gravitational systems of units (British Type II and Metric Type II; see par 4-3.2) *cannot* be used in Eq. 4-39. This is because there is a fundamental difference in the way the unit of force is defined in the gravitational systems. The quantities of these systems (see Table 4-7) must be used in Eqs. 4-26 or 4-27. Quantities expressed in gravitational units must be converted using unit conversion equalities in Table 5-1 for use in the SI. There are few situations in which there are fundamental differences in the definitions of units such as occurs with force, mass, and acceleration.

TABLE 4-7
COMBINATIONS OF UNITS THAT CAN BE USED
IN THE EQUATION $g_oF = ma$

Force	Mass	Acceleration
pound-force	pound-mass	foot per second²
kilogram-force	kilogram-mass	metre per second²

Consider again the equation for inductance (Eq. 4-37) of a solenoid having a diameter-to-length ratio of one:

$$L\ \mu\text{H} = 0.0173\ (\mu\text{H/in.})\ n^2 d \text{ in.} \tag{4-42}$$

This equation can be converted to SI units by converting the numerical factor to SI units and by expressing L and d in henries and metres, respectively. From Table 5-1 and 3-2:

$$1 \text{ H} = 10^6\ \mu\text{H}$$

$$1 \text{ in.} = 0.0254 \text{ m}$$

The unit conversion factors needed are:

$$1 = \frac{\text{H}}{10^6\ \mu\text{H}}$$

$$1 = \frac{\text{in.}}{0.0254 \text{ m}}$$

The numerical factor is converted to SI in the following manner:

$$0.0173 \frac{\mu\text{H}}{\text{in.}} \times \frac{\text{H}}{10^6\,\mu\text{H}} \times \frac{\text{in.}}{0.0254\text{ m}} = 6.811\,023 \times 10^{-7}\text{ H/m}$$

Rounding this constant to three significant digits and using the appropriate units with L and d, Eq. 4-42 becomes:

$$L\text{ H} = \left[6.81 \times 10^{-7}\text{ (H/m)}\right] n^2 d\text{ m}$$

or

$$L = 6.81 \times 10^{-7}\, n^2 d,\text{ H}$$

where d is expressed in metres.

For $d = 10$ mm $= 10^{-2}$ m and $n = 100 = 10^2$

$$L = 6.81 \times 10^{-7} \times 10^4 \times 10^{-2} = 6.81 \times 10^{-5}\text{ H} = 68.1\ \mu\text{H}$$

It is worthwhile to check at least one calculation with the original equation. The diameter $d = 10^{-2}$ m is converted as follows:

$$d = 10^{-2}\text{ m} \times \frac{\text{in.}}{0.0254\text{ m}} = 3.94 \times 10^{-1}\text{ in.}$$

Substituting $d = 0.394$ in. and $n^2 = 10^4$ into Eq. 4-42 gives:

$$L = 0.0173 \frac{\mu\text{H}}{\text{in.}} \times 10^4 \times 0.394\text{ in.} = 68.1\ \mu\text{H}$$

Before leaving this example, it is probably useful to indicate another approach to converting Eq. 4-33 to SI units. This is done by introducing a numerical factor of one on the right-hand side of Eq. 4-43 and associating the hidden units with that factor, i.e.,

$$L\,\mu\text{H} = 1 \frac{\mu\text{H}}{\text{in.}}\ F n^2 d\text{ in.} \tag{4-43}$$

The factor of one with its units, μH/in., is converted to SI units in the following manner:

$$1 \frac{\mu\text{H}}{\text{in.}} \times \frac{\text{H}}{10^6\,\mu\text{H}} \times \frac{\text{in.}}{0.0254\text{ m}} = 3.94 \times 10^{-5}\text{ H/m}$$

Thus, the equation can be written:

$$L\text{ H} = 3.94 \times 10^{-5}\, F n^2 d\text{ H} \tag{4-44}$$

The advantage is that F, the form-factor, appears explicitly in the equation. Since F depends on a ratio of lengths (diameter to coil length) which is independent of units and since F is, in this case, a dimensionless number, Eq. 4-44 is as general as the original expression. Values of the form-factor can be determined in the same manner (Ref. 9). Further examples of the conversion of equations to SI units are presented in the examples that follow:

Example No. 12: Convert to SI units the following formula which allows the calculation of breaking loads W for crane chains (Ref. 10):

$$W = 54\,000\, D^2,\text{ lb}$$

where D is the diameter in inches of the wire material from which the chain is made.

a. In this example, pound is a weight or force and it is assumed that the equation is to be used in the British Type I system.

b. The equation with appropriate units is:

$$W\text{ lb} = 54\,000\, D^2\text{ in.}^2$$

Thus there are hidden units associated with the numerical factor 54 000. The hidden units are identified by solving the equation for 54 000; i.e., dividing the equation by D^2 in.^{2}:

$$54\,000 = \frac{W \text{ lb}}{D^2 \text{ in.}^2}$$

Thus the units of 54 000 are lb/in.^{2}

c. The equation is converted to SI units by converting the numerical factor to SI units and using SI units for W and D. The unit equalities are obtained from Table 5-1:

$$1 \text{ in.} = 0.0254 \text{ m}$$
$$1 \text{ lb} = 4.448 \text{ N}$$

These equalities are used to form the unit conversion factors and the numerical factor is converted as follows:

$$54\,000 \frac{\text{lb}}{\text{in.}^2} \times \left(\frac{\text{in.}}{0.0254 \text{ m}}\right)^2 \times \frac{4.448 \text{ N}}{\text{lb}} = 3.723 \times 10^8 \frac{\text{N}}{\text{m}^2}$$

d. The converted equation is:

$$W \text{ N} = \left[3.723 \times 10^8 \text{ (N/m}^2)\right] D^2 \text{ m}^2$$

or

$$W = 3.723 \times 10^8 \, D, \text{ N}$$

where D is expressed in metres.

Example No. 13: Convert the ESU equation for the force between two electric charges to SI.

a. From par. 4-6, the ESU equation is:

$$F = \frac{1}{\epsilon} \left(\frac{Q_1 Q_2}{d^2}\right)$$

where F is force in dynes, Q_1 and Q_2 are electric charges in statcoulombs (assumed of opposite polarity to give positive/attractive force), d is separation in centimetres, and ϵ is permittivity of free space; in ESU, ϵ equals one.

b. The units of the numerical factor are found by solving the equation for $1/\epsilon$. (Note that $1/\epsilon$ is the factor which will be converted to SI.)

$$\frac{1}{\epsilon} = F \text{dyn} \times \frac{d^2 \text{ cm}^2}{Q_1 Q_2 \text{ statcoul}^2}$$

Thus the units of $1/\epsilon$ are dyne • cm^2/statcoul^2.

c. The factor $1/\epsilon$ is converted to SI as follows:

$$1 \text{ dyn} = 1 \times 10^{-5} \text{ N}$$
$$1 \text{ cm} = 10^{-2} \text{ m}$$
$$1 \text{ statcoul} = 3.335\,640 \times 10^{-10} \text{ C}$$

$$\frac{1}{\epsilon} = \frac{\text{dyn} \bullet \text{cm}^2}{\text{statcoul}^2} \times \left(\frac{\text{statcoul}}{3.335\,640 \times 10^{-10} \text{ C}}\right)^2 \times \left(\frac{10^{-2} \text{ m}}{\text{cm}}\right)^2 \times \frac{1 \times 10^{-5} \text{ N}}{\text{dyn}}$$

$$= 8.987\,556\,92 \times 10^9 \text{ N} \bullet \text{m}^2/\text{C}^2$$

d. Thus, the equation in SI units is:

$$F \text{N} = \left[8.987\,557 \times 10^9 \, \frac{\text{N} \bullet \text{m}^2}{\text{C}^2}\right] \frac{Q_1 Q_2 \text{ C}^2}{d^2 \text{ m}^2}$$

or

$$F = 8.987\,557 \times 10^9 \, \frac{Q_1 Q_2}{d^2}, \text{N}$$

where Q_1 and Q_2 are expressed in coulombs, and d is expressed in metres.
The numerical factor in this equation given in physics textbooks is $1/(4\pi\epsilon_0)$ where ϵ_0 is the permittivity of free space in SI units. Note that the factor 4π occurs because the SI is a rationalized system. Evaluating this factor gives (ϵ_0 is given in Table 4-5):

$$\frac{1}{4\pi\epsilon_0} = \frac{1}{4\pi(8.854\,185\,3 \times 10^{-12}\ \mathrm{C^2 \cdot J^{-1} \cdot m^{-1}})}$$

or

$$= 8.987\,554\,343 \times 10^{9}\ \mathrm{J \cdot m/C^2}$$

$$= 8.987\,554 \times 10^{9}\ \mathrm{N \cdot m^2/C^2}$$

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CHAPTER 5
CONVERSION FACTORS, MEASURED CONSTANTS, AND DIMENSIONLESS CONSTANTS

Conversion factors for converting quantities expressed in non-SI units to quantities expressed in SI units are presented in Table 5-1 and Table 5-2. These factors are taken from two major compilations of factors for conversion to SI units (Refs. 1 and 2). The factors, as they appear in this handbook, are given in the form of unit equalities (i.e., 1 inch = 0.0254 metre) rather than in the "to convert from . . . to . . . multiply by" format of the references. In Table 5-1 the conversion factors are listed alphabetically by non-SI units. The conversion factors in Table 5-2 are grouped according to physical quantity; i.e., length, mass, etc. The unit equalities which are exact are identified in Tables 5-1 and 5-2 by an asterisk (*) at the right-hand side of the page. Methods for converting units using the conversion factors in Table 5-1 and Table 5-2 are given in Chapter 4 and more specifically in pars. 4-1 and 4-4.

In Tables 5-1 and 5-2 the terminology pound-mass, pound-force, etc. is used to avoid ambiguity. Pound-force is the unit of force in the British Type II system and it is equal to the force unit, the pound, in the British Type I system. The pound-mass is the mass unit in the British Type II system and it is equal to the mass unit, the pound, in the foot-pound-second (FPS) system (see par. 4-3.2). Pound, by itself, is not used in the tables because it is a force unit in the British Type I system and it is a mass unit in the FPS system.

Table 5-3 (Ref. 1) lists experimentally determined constants expressed in SI units and frequently used in scientific and technical calculations. Table 5-4 (Ref. 1) lists dimensionless constants frequently used in scientific calculations.

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TABLE 5-1

UNIT EQUALITIES—ALPHABETICAL LISTING

1 abampere	=	$1.00 \times 10^{+1}$	ampere (A)	*
1 abcoulomb	=	$1.00 \times 10^{+1}$	coulomb (C)	*
1 abfarad	=	$1.00 \times 10^{+9}$	farad (F)	*
1 abhenry	=	1.00×10^{-9}	henry (H)	*
1 abmho	=	$1.00 \times 10^{+9}$	siemens (S)	*
1 abohm	=	1.00×10^{-9}	ohm (Ω)	*
1 abvolt	=	1.00×10^{-8}	volt (V)	*
1 acre-foot	=	$1.233\ 482 \times 10^{+3}$	metre^3 (m^3)	
1 acre	=	$4.046\ 856\ 422\ 4 \times 10^{+3}$	metre^2 (m^2)	*
1 ampere (A) (international of 1948)	=	$9.998\ 43 \times 10^{-1}$	ampere (A)	
1 ampere (U.S. legal 1948)	=	1.000 008	ampere (A)	
1 ampere-hour	=	$3.600 \times 10^{+3}$	coulomb (C)	*
1 angstrom (Å)	=	1.00×10^{-10}	metre (m)	*
1 are (a)	=	$1.00 \times 10^{+2}$	metre^2 (m^2)	*
1 astronomical unit (AU)	=	$1.495\ 978\ 9 \times 10^{+11}$	metre (m)	
1 atmosphere (atm) (normal)	=	$1.013\ 25 \times 10^{+5}$	pascal (Pa)	*
1 atmosphere (technical = 1 kgf/cm^2)	=	$9.806\ 650 \times 10^{+4}$	pascal (Pa)	*
1 bar	=	$1.00 \times 10^{+5}$	pascal (Pa)	*
1 barn (b)	=	1.00×10^{-28}	metre^2 (m^2)	*
1 barrel (bbl) (petroleum, 42 gal)	=	$1.589\ 873 \times 10^{-1}$	metre^3 (m^3)	
1 board foot	=	$2.359\ 737 \times 10^{-3}$	metre^3 (m^3)	
1 barye	=	1.00×10^{-1}	pascal (Pa)	*

TABLE 5-1 (cont'd)

1	British thermal unit (Btu) (ISO/TC 12)	=	$1.055\ 06 \times 10^{+3}$	joule (J)
1	British thermal unit (International Steam Table)	=	$1.055\ 04 \times 10^{+3}$	joule (J)
1	British thermal unit (mean)	=	$1.055\ 87 \times 10^{+3}$	joule (J)
1	British thermal unit (thermochemical)	=	$1.054\ 350\ 264\ 488 \times 10^{+3}$	joule (J)
1	British thermal unit (39°F)	=	$1.059\ 67 \times 10^{+3}$	joule (J)
1	British thermal unit (60°F)	=	$1.054\ 68 \times 10^{+3}$	joule (J)
1	Btu (thermochemical)/(foot^2-second)	=	$1.134\ 893 \times 10^{+4}$	watt/metre^2 (W/m^2)
1	Btu (thermochemical)/(foot^2-minute)	=	$1.891\ 489 \times 10^{+2}$	watt/metre^2 (W/m^2)
1	Btu (thermochemical)/(foot^2-hour)	=	3.152 481	watt/metre^2 (W/m^2)
1	Btu (thermochemical)/(inch^2-second)	=	$1.634\ 246 \times 10^{+6}$	watt/metre^2 (W/m^2)
1	Btu (thermochemical)-inch/(second-foot^2-°F) (k, thermal conductivity)	=	$5.188\ 732 \times 10^{+2}$	watt/(metre kelvin) (W/m•K)
1	Btu (International Table)-inch/(second-foot^2-°F) (k, thermal conductivity)	=	$5.192\ 204 \times 10^{+2}$	watt/(metre-kelvin) (W/m•K)
1	Btu (thermochemical)-inch/(hour-foot^2-°F) (k, thermal conductivity)	=	$1.441\ 314 \times 10^{-1}$	watt/(metre-kelvin) (W/m•K)
1	Btu (International Table)-inch/(hour-foot^2-°F) (k, thermal conductivity)	=	$1.442\ 279 \times 10^{-1}$	watt/(metre kelvin) (W/m•K)
1	Btu (International Table)/foot^2	=	$1.135\ 653 \times 10^{+4}$	joule/metre^2 (J/m^2)
1	Btu (thermochemical)/foot^2	=	$1.134\ 893 \times 10^{+4}$	joule/metre^2 (J/m^2)

TABLE 5-1 (cont'd)

1	Btu (International Table)/(hour-foot^2-°F) (*C*, thermal conductance)	=	5.678 263	watt/(metre^2-kelvin) (W/m^2 • K)	
1	Btu (thermochemical)/(hour-foot^2-°F) (*C*, thermal conductance)	=	5.674 466	watt/(metre^2-kelvin) (W/m^2 • K)	
1	Btu (International Table)/pound-mass	=	$2.326 \times 10^{+3}$	joule/kilogram (J/kg)	*
1	Btu (thermochemical)/pound-mass	=	$2.324\ 444 \times 10^{+3}$	joule/kilogram (J/kg)	
1	Btu (International Table)/(pound mass-°F) (*c*, heat capacity)	=	$4.186\ 800 \times 10^{+3}$	joule/(kilogram-kelvin) (J/kg • K)	*
1	Btu (thermochemical)/(pound mass-°F) (*c*, heat capacity)	=	$4.184\ 000 \times 10^{+3}$	joule/(kilogram-kelvin) (J/kg • K)	
1	Btu (International Table)/(second-foot^2-°F)	=	$2.044\ 175 \times 10^{+4}$	watt/(metre^2-kelvin) (W/m^2 • K)	
1	Btu (thermochemical)/(second-foot^2-°F	=	$2.042\ 808 \times 10^{+4}$	watt/(metre^2-kelvin) (W/m^2 • K)	
1	Btu (International Table)/hour	=	$2.930\ 711 \times 10^{-1}$	watt (W)	
1	Btu (thermochemical)/second	=	$1.054\ 350 \times 10^{+3}$	watt (W)	
1	Btu (thermochemical)/minute	=	$1.757\ 250 \times 10^{+1}$	watt (W)	
1	Btu (thermochemical)/hour	=	$2.928\ 751 \times 10^{-1}$	watt (W)	
1	bushel (U.S.)	=	$3.523\ 907\ 016\ 688 \times 10^{-2}$	metre^3 (m^3)	*
1	cable	=	$2.194\ 56 \times 10^{+2}$	metre (m)	*
1	caliber	=	2.54×10^{-4}	metre (m)	*
1	calorie (cal) (International Steam Table)	=	4.1868	joule (J)	

TABLE 5-1 (cont'd)

1 calorie (mean)	=	4.190 02	joule (J)	
1 calorie (thermochemical)	=	4.184	joule (J)	*
1 calorie (15°C)	=	4.185 80	joule (J)	
1 calorie (20°C)	=	4.181 90	joule (J)	
1 calorie (kilogram, International Steam Table)	=	$4.1868 \times 10^{+3}$	joule (J)	
1 calorie (kilogram, mean)	=	$4.190\ 02 \times 10^{+3}$	joule (J)	
1 calorie (kilogram, thermochemical)	=	$4.184 \times 10^{+3}$	joule (J)	*
1 cal (thermochemical)/(centimetre^2-minute)	=	$6.973\ 333 \times 10^{+2}$	watt/metre^2 (W/m^2)	
1 cal (thermochemical)/centimetre^2	=	$4.184 \times 10^{+4}$	joule/metre^2 (J/m^2)	*
1 cal (thermochemical)/(centimetre^2-second)	=	$4.184 \times 10^{+4}$	watt/metre^2 (W/m^2)	*
1 cal (thermochemical)/(centimetre-second-°C)	=	$4.184 \times 10^{+2}$	watt/(metre-kelvin) (W/m • K)	*
1 cal (International Table)/gram	=	$4.186\ 800 \times 10^{+3}$	joule/kilogram (J/kg)	*
1 cal (International Table)/(gram-°C)	=	$4.186\ 800 \times 10^{+3}$	joule/(kilogram-kelvin) (J/kg • K)	*
1 cal (thermochemical)/gram	=	$4.184 \times 10^{+3}$	joule/kilogram (J/kg)	*
1 cal (thermochemical)/(gram-°C)	=	$4.184 \times 10^{+3}$	joule/(kilogram-kelvin) (J/kg • K)	*
1 cal (thermochemical)/second	=	4.184	watt (W)	*
1 cal (thermochemical)/minute	=	$6.973\ 333 \times 10^{-2}$	watt (W)	

TABLE 5-1 (cont'd)

1 carat	=	2.00×10^{-4}	kilogram (kg)	*
1 centimetre of mercury (0°C)	=	$1.333\ 22 \times 10^{+3}$	pascal (Pa)	
1 centimetre of water (4°C)	=	$9.806\ 38 \times 10^{+1}$	pascal (Pa)	
1 centipoise	=	1.00×10^{-3}	pascal-second (Pa • s)	*
1 centistoke	=	1.00×10^{-6}	metre^2/second (m^2/s)	*
1 chain (engineer or ramden)	=	$3.048 \times 10^{+1}$	metre (m)	*
1 chain (surveyor or gunter)	=	$2.011\ 68 \times 10^{+1}$	metre (m)	*
1 circular mil	=	$5.067\ 074\ 8 \times 10^{-10}$	metre^2 (m^2)	
1 clo	=	$2.003\ 712 \times 10^{-1}$	kelvin-metre^2/watt ($K \bullet m^2/W$)	
1 cord	=	3.624 556 3	metre^3 (m^3)	
1 coulomb (C) (International of 1948)	=	$9.998\ 43 \times 10^{-1}$	coulomb (C)	
1 coulomb (U.S. Legal 1948)	=	1.000 008	coulomb (C)	
1 cubit	=	4.572×10^{-1}	metre (m)	*
1 cup	=	$2.365\ 882\ 365 \times 10^{-4}$	metre^3 (m^3)	*
1 curie (Ci)	=	$3.70 \times 10^{+10}$	disintegrations/second	*
1 day (mean solar)	=	$8.64 \times 10^{+4}$	second (s) (mean solar)	*
1 day (sidereal)	=	$8.616\ 409\ 0 \times 10^{+4}$	second (s) (mean solar)	
1 decibar	=	$1.00 \times 10^{+4}$	pascal (Pa)	*

TABLE 5-1 (cont'd)

1	degree (deg) (angle)	=	$1.745\ 329\ 251\ 994\ 3 \times 10^{-2}$..	radian (rad)	
1	°F-hour-foot^2/Btu (thermochemical) (R, thermal resistance)	=	$1.762\ 280 \times 10^{-1}$	kelvin-metre^2/watt ($K \bullet m^2/W$)	*
1	°F-hour-foot^2/Btu (International Table) (R, thermal resistance)	=	$1.761\ 102 \times 10^{-1}$	kelvin-metre^2/watt ($K \bullet m^2/W$)	
1	denier (international)	=	1.00×10^{-7}	kilogram/metre (kg/m)	*
1	dram (avoirdupois)	=	$1.771\ 845\ 195\ 312\ 5 \times 10^{-3}$	kilogram (kg)	*
1	dram (troy or apothecary)	=	$3.887\ 934\ 6 \times 10^{-3}$	kilogram (kg)	*
1	dram (U.S. fluid)	=	$3.696\ 691\ 195\ 312\ 5 \times 10^{-6}$	metre^3 (m^3)	*
1	dyne (dyn)	=	1.00×10^{-5}	newton (N)	*
1	dyne-centimetre	=	1.00×10^{-7}	newton-metre ($N \bullet m$)	*
1	dyne per centimetre^2	=	1.00×10^{-1}	pascal (Pa)	*
1	electron volt (eV)	=	$1.602\ 10 \times 10^{-19}$	joule (J)	
1	EMU of capacitance	=	$1.00 \times 10^{+9}$	farad (F)	*
1	EMU of current	=	$1.00 \times 10^{+1}$	ampere (A)	*
1	EMU of electric potential	=	1.00×10^{-8}	volt (V)	*
1	EMU of inductance	=	1.00×10^{-9}	henry (H)	*
1	EMU of resistance	=	1.00×10^{-9}	ohm (Ω)	*
1	erg	=	1.00×10^{-7}	joule (J)	*
1	erg/centimetre^2-second	=	1.00×10^{-3}	watt/metre^2 (W/m^2)	*

TABLE 5-1 (cont'd)

1 erg/second	=	1.00×10^{-7}	watt (W) *
1 ESU of capacitance	=	$1.112\ 650 \times 10^{-12}$	farad (F)
1 ESU of current	=	$3.335\ 6 \times 10^{-10}$	ampere (A)
1 ESU of electrical potential	=	$2.997\ 9 \times 10^{+2}$	volt (V)
1 ESU of inductance	=	$8.987\ 554 \times 10^{+11}$	henry (H)
1 ESU of resistance	=	$8.987\ 554 \times 10^{+11}$	ohm (Ω)
1 farad (F) (international U.S.)	=	$9.995\ 05 \times 10^{-1}$	farad (F)
1 faraday (based on carbon-12)	=	$9.648\ 70 \times 10^{+4}$	coulomb (C)
1 faraday (chemical)	=	$9.649\ 57 \times 10^{+4}$	coulomb (C)
1 faraday (physical)	=	$9.652\ 19 \times 10^{+4}$	coulomb (C)
1 fathom	=	1.8288	metre (m) *
1 fermi (femtometre)	=	1.00×10^{-15}	metre (m) *
1 fluid ounce (U.S.)	=	$2.957\ 352\ 956\ 25 \times 10^{-5}$	metre^3 (m^3) *
1 foot (ft)	=	3.048×10^{-1}	metre (m) *
1 foot (U.S. survey)	=	$3.048\ 006\ 096 \times 10^{-1}$	metre (m)
1 foot^3/minute	=	$4.719\ 474 \times 10^{-4}$	metre^3/second (m^3/s)
1 foot^3/second	=	$2.831\ 685 \times 10^{-2}$	metre^3/second (m^3/s)
1 foot^3	=	$2.831\ 685 \times 10^{-2}$	metre^3 (m^3)
1 foot^2	=	$9.290\ 304 \times 10^{-2}$	metre^2 (m^2) *
1 foot/hour	=	$8.466\ 667 \times 10^{-5}$	metre/second (m/s)
1 foot/minute	=	5.080×10^{-3}	metre/second (m/s) *
1 foot/second	=	3.048×10^{-1}	metre/second (m/s) *

TABLE 5-1 (cont'd)

1	$foot^2$/second	=	$9.290\ 304 \times 10^{-2}$	$metre^2$/second (m^2/s) *
1	foot of water (39.2 °F)	=	$2.988\ 98 \times 10^{+3}$	pascal (Pa)
1	foot-candle (fc)	=	$1.076\ 391 \times 10^{+1}$	lumen/$metre^2$ (lm/m^2)
1	foot-candle (fc)	=	$1.076\ 391 \times 10^{+1}$	lux (lx)
1	foot-lambert (ft L)	=	3.426 259	candela/$metre^2$ (cd/m^2)
1	foot-pound-force	=	1.355 818	joule (J)
1	foot-pound-force/hour	=	$3.766\ 161 \times 10^{-4}$	watt (W)
1	foot-pound-force/minute	=	$2.259\ 697 \times 10^{-2}$	watt (W)
1	foot-pound-force/second	=	1.355 818	watt (W)
1	foot-poundal	=	$4.214\ 011 \times 10^{-2}$	joule (J)
1	$foot^2$/hour (thermal diffusivity)	=	$2.580\ 640 \times 10^{-5}$	$metre^2$/second (m^2/s) *
1	foot/$second^2$	=	3.048×10^{-1}	metre/$second^2$ (m/s^2) *
1	free fall, standard	=	9.806 650	metre/$second^2$ (m/s^2) *
1	furlong	=	$2.011\ 68 \times 10^{+2}$	metre (m) *
1	galileo (Gal)	=	1.00×10^{-2}	metre/$second^2$ (m/s^2) *
1	gallon (gal) (Canadian liquid)	=	$4.546\ 090 \times 10^{-3}$	$metre^3$ (m^3)
1	gallon (U.K. liquid)	=	$4.546\ 087 \times 10^{-3}$	$metre^3$ (m^3)
1	gallon (U.S. dry)	=	$4.404\ 883\ 770\ 86 \times 10^{-3}$	$metre^3$ (m^3) *
1	gallon (U.S. liquid)	=	$3.785\ 411\ 784 \times 10^{-3}$	$metre^3$ (m^3) *
1	gallon (U.S. liquid)/day	=	$4.381\ 264 \times 10^{-8}$	$metre^3$/second (m^3/s)

TABLE 5-1 (cont'd)

1	gallon (U.S. liquid)/ minute	=	$6.309\ 020 \times 10^{-5}$	metre^3/second (m^3/s)	
1	gamma (γ)	=	1.00×10^{-9}	tesla (T) *
1	gauss (Gs)	=	1.00×10^{-4}	tesla (T) *
1	gilbert (Gb)	=	$7.957\ 747\ 2 \times 10^{-1}$	ampere turn
1	gill (U.K.)	=	$1.420\ 652 \times 10^{-4}$	metre^3 (m^3)
1	gill (U.S.)	=	$1.182\ 941\ 2 \times 10^{-4}$	metre^3 (m^3)
1	grad	=	9.00×10^{-1}	degree (angular) *
1	grad	=	$1.570\ 796\ 3 \times 10^{-2}$	radian (rad)
1	grain (lbm avoirdupois/ 7000)	=	$6.479\ 891 \times 10^{-5}$	kilogram (kg) *
1	grain (lbm avoirdupois/ 7000)/gallon (U.S. liquid)	=	$1.711\ 806 \times 10^{-2}$	kilogram/metre^3 (kg/m^3)
1	gram (g)	=	1.00×10^{-3}	kilogram (kg) *
1	gram/centimetre^3	=	$1.00 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)
1	gram-force*/centimetre^2	=	$9.806\ 650 \times 10^{+1}$	pascal (Pa) *
1	hand	=	1.016×10^{-1}	metre (m) *
1	hectare	=	$1.00 \times 10^{+4}$	metre^2 (m^2) *
1	henry (H) (international of 1948)	=	1.000 495	henry (H)
1	hogshead (U.S.)	=	$2.384\ 809\ 423\ 92 \times 10^{-1}$	metre^3 (m^3) *
1	horsepower (550 ft • lbf/s)	=	$7.456\ 998\ 7 \times 10^{+2}$	watt (W)
1	horsepower (boiler)	=	$9.809\ 50 \times 10^{+3}$	watt (W)

*1 gram-force = 980.665 dynes means that a gram-mass experiences a force of 980.665 dynes in the earth's gravitational field.

TABLE 5-1 (cont'd)

1 horsepower (electric)	=	$7.46 \times 10^{+2}$	watt (W)	*
1 horsepower (metric)	=	$7.354\ 99 \times 10^{+2}$	watt (W)	
1 horsepower (U.K.)	=	$7.457 \times 10^{+2}$	watt (W)	
1 horsepower (water)	=	$7.460\ 43 \times 10^{+2}$	watt (W)	
1 hour (h) mean solar	=	$3.60 \times 10^{+3}$	second (mean solar) (s)	*
1 hour (sidereal)	=	$3.590\ 170\ 4 \times 10^{+3}$	second (mean solar) (s)	
1 hundredweight (long)	=	$5.080\ 234\ 544 \times 10^{+1}$	kilogram (kg)	*
1 hundredweight (short)	=	$4.535\ 923\ 7 \times 10^{+1}$	kilogram (kg)	*
1 inch (in.)	=	2.54×10^{-2}	metre (m)	*
1 inch^2	=	$6.451\ 600 \times 10^{-4}$	metre^2 (m^2)	*
1 inch^3	=	$1.638\ 706 \times 10^{-5}$	metre^3 (m^3)	
1 inch^3/minute	=	$2.731\ 177 \times 10^{-7}$	metre^3/second (m^3/s)	
1 inch/second	=	2.540×10^{-2}	metre/second (m/s)	*
1 inch of mercury (32°F)	=	$3.386\ 389 \times 10^{+3}$	pascal (Pa)	
1 inch of mercury (60°F)	=	$3.376\ 85 \times 10^{+3}$	pascal (Pa)	
1 inch of water (39.2°F)	=	$2.490\ 82 \times 10^{+2}$	pascal (Pa)	
1 inch of water (60°F)	=	$2.4884 \times 10^{+2}$	pascal (Pa)	
1 inch/second^2	=	2.540×10^{-2}	metre/second^2 (m/s^2)	*
1 joule (J) (international of 1948)	=	1.000 165	joule (J)	
1 joule (J) (U.S. legal 1948)	=	1.000 017	joule (J)	

TABLE 5-1 (cont'd)

1 kayser	=	$1.00 \times 10^{+2}$	1/metre (1/m)	*
1 kilocalorie (kcal) (International Steam Table)	=	$4.186\ 74 \times 10^{+3}$	joule (J)	
1 kilocalorie (mean)	=	$4.190\ 02 \times 10^{+3}$	joule (J)	
1 kilocalorie (thermo-chemical)	=	$4.184 \times 10^{+3}$	joule (J)	*
1 kilocalorie (thermo-chemical)/minute	=	$6.973\ 333 \times 10^{+1}$	watt (W)	
1 kilocalorie (thermo-chemical)/second	=	$4.184 \times 10^{+3}$	watt (W)	*
1 kilogram-force (kgf)*	=	9.806 650	newton (N)	*
1 kilogram-force-metre	=	9.806 650	newton-metre (N • m)	*
1 kilogram-force-second^2/metre (mass)	=	9.806 650	kilogram (kg)	*
1 kilogram-force/centimetre^2	=	$9.806\ 650 \times 10^{+4}$	pascal (Pa)	*
1 kilogram-force/metre^2	=	9.806 650	pascal (Pa)	*
1 kilogram-force/millimetre^2	=	$9.806\ 650 \times 10^{+6}$	pascal (Pa)	*
1 kilogram mass	=	1.00	kilogram (kg)	*
1 kilometre/hour	=	$2.777\ 778 \times 10^{-1}$	metre/second (m/s)	
1 kilopond force	=	9.806 65	newton (N)	*
1 kilowatt-hour	=	$3.600 \times 10^{+6}$	joule (J)	*
1 kilowatt-hour (international U.S.)	=	$3.600\ 655 \times 10^{+6}$	joule (J)	
1 kilowatt-hour (U.S. legal 1948)	=	$3.600\ 061 \times 10^{+6}$	joule (J)	
1 kip (1000 lbf)	=	$4.448\ 221\ 615\ 260\ 5 \times 10^{+3}$	newton (N)	*

*Means that a kilogram-mass experiences a force of 9.806 650 N in the earth's gravitational field.

TABLE 5-1 (cont'd)

1 kip/inch^2 (ksi)	=	$6.894\ 757 \times 10^{+6}$	pascal (Pa)	
1 knot (kn) (international)	=	$5.144\ 444\ 444 \times 10^{-1}$	metre/second (m/s)	
1 lambert (L)	=	$(1/\pi) \times 10^{+4}$	candela/metre^2 (cd/m^2)	*
1 lambert (L)	=	$3.183\ 098\ 8 \times 10^{+3}$	candela/metre^2 (cd/m^2)	
1 langley	=	$4.184 \times 10^{+4}$	joule/metre^2 (J/m^2)	*
1 league (British nautical)	=	$5.559\ 552 \times 10^{+3}$	metre (m)	*
1 league (international nautical)	=	$5.556 \times 10^{+3}$	metre (m)	*
1 league (statute)	=	$4.828\ 032 \times 10^{+3}$	metre (m)	*
1 league (U.K. nautical)	=	$5.559\ 552 \times 10^{+3}$	metre (m)	*
1 light year (ly)	=	$9.460\ 55 \times 10^{+15}$	metre (m)	
1 link (engineer or ramden)	=	3.048×10^{-1}	metre (m)	*
1 link (surveyor or gunter)	=	$2.011\ 68 \times 10^{-1}$	metre (m)	*
1 litre (l)	=	1.00×10^{-3}	metre^3 (m^3)	*
1 lux (lx)	=	1.00	lumen/metre^2 (lm/m^2)	*
1 maxwell (Mx)	=	1.00×10^{-8}	weber (Wb)	*
1 metre (m)	=	$1.650\ 763\ 73 \times 10^{+6}$	wavelengths Kr 86	*
1 microinch	=	2.540×10^{-8}	metre (m)	*
1 micron	=	1.00×10^{-6}	metre (m)	*
1 mil	=	2.54×10^{-5}	metre (m)	*
1 mile (mi) (international nautical)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 mile (U.K. nautical)	=	$1.853\ 184 \times 10^{+3}$	metre (m)	*

TABLE 5-1 (cont'd)

1 mile (U.S. nautical)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 mile (U.S. statute)	=	$1.609\ 344 \times 10^{+3}$	metre (m)	*
1 mile^2 (U.S. statute)	=	$2.589\ 988 \times 10^{+6}$	metre^2 (m^2)	
1 mile/hour (U.S. statute)	=	$4.470\ 400 \times 10^{-1}$	metre/second (m/s)	*
1 mile/minute (U.S. statute)	=	$2.682\ 240 \times 10^{+1}$	metre/second (m/s)	*
1 mile/second (U.S. statute)	=	$1.609\ 344 \times 10^{+3}$	metre/second (m/s)	*
1 mile/hour (U.S. statute)	=	1.609 344	kilometre/hour	*
1 millibar	=	$1.00 \times 10^{+2}$	pascal (Pa)	*
1 millimetre of mercury (0°C)	=	$1.333\ 224 \times 10^{+2}$	pascal (Pa)	
1 minute (min) (angle)	=	$2.908\ 882\ 086\ 66 \times 10^{-4}$	radian (rad)	
1 minute (min) (mean solar)	=	$6.00 \times 10^{+1}$	second (s) (mean solar)	*
1 minute (sidereal)	=	$5.983\ 617\ 4 \times 10^{+1}$	second (s) (mean solar)	
1 moment of inertia (lbm • ft^2)	=	$4.214\ 012 \times 10^{-2}$	kilogram-metre^2 (kg • m^2)	
1 moment of inertia (lbm • in^2)	=	$2.926\ 397 \times 10^{-5}$	kilogram-metre^2 (kg • m^2)	
1 moment of section (second moment of area) (ft^4)	=	$8.630\ 975 \times 10^{-3}$	metre^4 (m^4)	
1 moment of section (second moment of area) (in.^{4})	=	$4.162\ 314 \times 10^{-7}$	metre^4 (m^4)	
1 month (mean calendar)	=	$2.628 \times 10^{+6}$	second (s) (mean solar)	*
1 nautical mile (nmi) (international)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 nautical mile (U.S.)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 nautical mile (U.K.)	=	$1.853\ 184 \times 10^{+3}$	metre (m)	*

TABLE 5-1 (cont'd)

1 oersted (Oe)	=	$7.957\ 747\ 2 \times 10^{+1}$	ampere/metre (A/m)	
1 ohm (Ω) (international of 1948)	=	1.000 495	ohm (Ω)	
1 ohm-centimetre	=	1.00×10^{-2}	ohm-metre ($\Omega \bullet m$)	*
1 ounce (U.K. fluid)	=	$2.841\ 307 \times 10^{-5}$	metre^3 (m^3)	
1 ounce (U.S. fluid)	=	$2.957\ 353 \times 10^{-5}$	metre^3 (m^3)	
1 ounce-force (avoirdupois)	=	$2.780\ 138\ 5 \times 10^{-1}$	newton (N)	
1 ounce-force-inch	=	$7.061\ 552 \times 10^{-3}$	newton-metre ($N \bullet m$)	
1 ounce-mass (avoirdupois)	=	$2.834\ 952\ 312\ 5 \times 10^{-2}$	kilogram (kg)	*
1 ounce-mass (troy or apothecary)	=	$3.110\ 347\ 68 \times 10^{-2}$	kilogram (kg)	*
1 ounce-mass/yard^2	=	$3.390\ 575 \times 10^{-2}$	kilogram/metre^2 (kg/m^2)	
1 ounce (avoirdupois)/ gallon (U.K. liquid)	=	6.236 027	kilogram/metre^3 (kg/m^3)	
1 ounce (avoirdupois)/ gallon (U.S. liquid)	=	7.489 152	kilogram/metre^3 (kg/m^3)	
1 ounce (avoirdupois) (mass)/inch^3	=	$1.729\ 994 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)	
1 pace	=	7.62×10^{-1}	metre (m)	*
1 parsec (ps)	=	$3.083\ 74 \times 10^{+16}$	metre (m)	
1 pascal (Pa)	=	1.00	newton/metre^2 (N/m^2)	*
1 peck (U.S.)	=	$8.809\ 767\ 541\ 72 \times 10^{-3}$	metre^3 (m^3)	*
1 pennyweight	=	$1.555\ 173\ 84 \times 10^{-3}$	kilogram (kg)	*
1 perch	=	5.0292	metre (m)	*

TABLE 5-1 (cont'd)

1 perm (0 °C)	=	5.721 35 x 10^{-11}	kilogram/(pascal-second-metre^2) (kg/Pa • s • m^2)	
1 perm (23 °C)	=	5.745 25 x 10^{-11}	kilogram/(pascal second-metre^2) (kg/Pa • s • m^2)	
1 perm-inch (0 °C)	=	1.453 22 x 10^{-12}	kilogram/(pascal-second-metre) (kg/Pa • s • m)	
1 perm-inch (23 °C)	=	1.459 29 x 10^{-12}	kilogram/(pascal-second-metre) (kg/Pa • s • m)	
1 phot	=	1.00 x 10^{+4}	lumen/metre^2 (lm/m^2)	*
1 pica (printer's)	=	4.217 517 6 x 10^{-3}	metre (m)	*
1 pint (pt) (U.S. dry)	=	5.506 104 713 575 x 10^{-4}	metre^3 (m^3)	*
1 pint (U.S. liquid)	=	4.731 764 73 x 10^{-4}	metre^3 (m^3)	*
1 point (printer's)	=	3.514 598 x 10^{-4}	metre (m)	*
1 poise (P)	=	1.00 x 10^{-1}	newton-second/metre^2 (N • s/m^2)	*
1 pole	=	5.0292	metre (m)	*
1 poundal (pdl)	=	1.382 549 543 76 x 10^{-1}	newton (N)	*
1 poundal/foot^2	=	1.488 164	pascal (Pa)	
1 poundal-second/foot^2	=	1.488 164	pascal-second (Pa • s)	
1 pound-force (lbf avoirdupois)	=	4.448 221 615 260 5	newton (N)	*
1 pound-force-inch	=	1.129 848 x 10^{-1}	newton-metre (N • m)	
1 pound-force-foot	=	1.355 818	newton-metre (N • m)	
1 pound-force-foot/inch	=	5.337 866 x 10^{+1}	newton-metre/metre (N • m/m)	
1 pound-force-inch/inch	=	4.448 222	newton-metre/metre (N • m/m)	

TABLE 5-1 (cont'd)

1 pound-force/inch	=	$1.751\ 268 \times 10^{+2}$	newton/metre (N/m)	
1 pound-force/foot	=	$1.459\ 390 \times 10^{+1}$	newton/metre (N/m)	
1 pound-force/foot^2	=	$4.788\ 026 \times 10^{+1}$	pascal (Pa)	
1 pound-force/inch^2 (psi)	=	$6.894\ 757 \times 10^{+3}$	pascal (Pa)	
1 pound-force-second/ foot^2	=	$4.788\ 026 \times 10^{+1}$	pascal-second (Pa • s)	
1 pound-mass (lbm avoirdupois)	=	$4.535\ 923\ 7 \times 10^{-1}$	kilogram (kg)	*
1 pound-mass (troy or apothecary)	=	$3.732\ 417\ 216 \times 10^{-1}$	kilogram (kg)	*
1 pound-mass/foot^2	=	4.882 428	kilogram/metre^2 (kg/m^2)	
1 pound-mass/second	=	$4.535\ 924 \times 10^{-1}$	kilogram/second (kg/s)	
1 pound-mass/minute	=	$7.559\ 873 \times 10^{-3}$	kilogram/second (kg/s)	
1 pound-mass/foot^3	=	$1.601\ 846 \times 10^{+1}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/inch^3	=	$2.767\ 990 \times 10^{+4}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/gallon (U. K. liquid)	=	$9.977\ 644 \times 10^{+1}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/gallon (U. S. liquid)	=	$1.198\ 264 \times 10^{+2}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/foot-second	=	1.488 164	pascal-second (Pa • s)	
1 quart (qt) (U.S. dry)	=	$1.101\ 220\ 942\ 715 \times 10^{-3}$	metre^3 (m^3)	*
1 quart (U.S. liquid)	=	$9.463\ 529\ 5 \times 10^{-4}$	metre^3 (m^3)	

TABLE 5-1 (cont'd)

1 rad (radiation dose absorbed)	=	1.00×10^{-2}	joule/kilogram (J/kg)	*
1 rayleigh (rate of photon emission)	=	$1.00 \times 10^{+10}$	1/(second-metre^2) (1/(s • m^2))	*
1 rhe	=	$1.00 \times 10^{+1}$	metre^2/(newton second) (m^2/(N • s))	*
1 rod	=	5.0292	metre (m)	*
1 roentgen (R)	=	$2.579\ 76 \times 10^{-4}$	coulomb/ kilogram (C/kg)	*
1 rutherford	=	$1.00 \times 10^{+6}$	disintegrations/ second	*
1 second (s) (angle)	=	$4.848\ 136\ 811 \times 10^{-6}$	radian (rad)	
1 second (s) (ephemeris)	=	1.00 000 000 0	second (s)	
1 second (mean solar)		Consult American Ephemeris and Nautical Almanac	second (ephemeris)	
1 second (sidereal)	=	$9.972\ 695\ 7 \times 10^{-1}$	second (s) (mean solar)	
1 section	=	$2.589\ 988\ 110\ 336 \times 10^{+6}$	metre^2 (m^2)	*
1 section modulus (ft^3)	=	$2.831\ 685 \times 10^{-2}$	metre^3 (m^3)	
1 section modulus (in.^{3})	=	$1.638\ 706 \times 10^{-5}$	metre^3 (m^3)	
1 scruple (apothecary)	=	$1.295\ 978\ 2 \times 10^{-3}$	kilogram (kg)	*
1 shake	=	1.00×10^{-8}	second (s)	*
1 skein	=	$1.097\ 28 \times 10^{+2}$	metre (m)	*
1 slug	=	$1.459\ 390\ 29 \times 10^{+1}$	kilogram (kg)	
1 slug/foot^3	=	$5.153\ 788 \times 10^{+2}$	kilogram/metre^3 (kg/m^3)	
1 slug/(foot-second)	=	$4.788\ 026 \times 10^{+1}$	pascal-second (Pa • s)	

TABLE 5-1 (cont'd)

1 span	=	2.286×10^{-1}	metre (m)	*
1 statampere	=	$3.335\ 640 \times 10^{-10}$	ampere (A)	
1 statcoulomb	=	$3.335\ 640 \times 10^{-10}$	coulomb (C)	
1 statfarad	=	$1.112\ 650 \times 10^{-12}$	farad (F)	
1 stathenry	=	$8.987\ 554 \times 10^{+11}$	henry (H)	
1 statmho	=	$1.112\ 650 \times 10^{-12}$	siemens (S)	
1 statohm	=	$8.987\ 554 \times 10^{+11}$	ohm (Ω)	
1 statute mile (U.S.)	=	$1.609\ 344 \times 10^{+3}$	metre (m)	*
1 statvolt	=	$2.997\ 925 \times 10^{+2}$	volt (V)	
1 stere (s)	=	1.00	metre^3 (m^3)	*
1 stilb (sb)	=	$1.00 \times 10^{+4}$	candela/metre^2 (cd/m^2)	*
1 stoke (St) (kinematic viscosity)	=	1.00×10^{-4}	metre^2/second (m^2/s)	*
1 tablespoon	=	$1.478\ 676\ 478\ 125 \times 10^{-5}$	metre^3 (m^3)	*
1 teaspoon	=	$4.928\ 921\ 593\ 75 \times 10^{-6}$	metre^3 (m^3)	*
1 tex	=	1.00×10^{-6}	kilogram/metre (kg/m)	*
1 ton (assay)	=	$2.916\ 666\ 6 \times 10^{-2}$	kilogram (kg)	
1 ton (long, 2240 lbm)	=	$1.016\ 046\ 908\ 8 \times 10^{+3}$	kilogram (kg)	*
1 ton (metric)	=	$1.00 \times 10^{+3}$	kilogram (kg)	*
1 ton (nuclear equivalent of TNT)	=	$4.20 \times 10^{+9}$	joule (J)	
1 ton (register)	=	2.831 684 659 2	metre^3 (m^3)	*
1 ton (short, 2000 lbm)	=	$9.071\ 847\ 4 \times 10^{+2}$	kilogram (kg)	*
1 ton (short, mass)/hour	=	$2.519\ 958 \times 10^{-1}$	kilogram/second (kg/s)	
1 ton (long, mass)/yard^3	=	$1.328\ 939 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)	

TABLE 5-1 (cont'd)

1 tonne	=	$1.00 \times 10^{+3}$	kilogram (kg)	*
1 torr (0 °C)	=	$1.333\ 22 \times 10^{+2}$	pascal (Pa)	
1 township	=	$9.323\ 957\ 2 \times 10^{+7}$	metre^2 (m^2)	
1 unit pole	=	$1.256\ 637 \times 10^{-7}$	weber (Wb)	
1 volt (V) (international of 1948)	=	1.000 330	volt (V)	
1 volt (U.S. legal 1948)	=	1.000 008	volt (V)	
1 watt (W) (international of 1948)	=	1.000 165	watt (W)	
1 watt (U.S. legal 1948)	=	1.000 017	watt (W)	
1 watt/centimetre^2	=	$1.00 \times 10^{+4}$	watt/metre^2 (W/m^2)	*
1 watt-hour	=	$3.600 \times 10^{+3}$	joule (J)	*
1 watt-second	=	1.00	joule (J)	*
1 yard (yd)	=	$9.144\ 000 \times 10^{-1}$	metre (m)	*
1 yard^2	=	$8.361\ 274 \times 10^{-1}$	metre^2 (m^2)	
1 yard^3	=	$7.645\ 549 \times 10^{-1}$	metre^3 (m^3)	
1 yard^3/minute	=	$1.274\ 258 \times 10^{-2}$	metre^3/second (m^3/s)	
1 year (yr) (calendar)	=	$3.1536 \times 10^{+7}$	second (s) (mean solar)	*
1 year (sidereal)	=	$3.155\ 815\ 0 \times 10^{+7}$	second (s) (mean solar)	
1 year (tropical)	=	$3.155\ 692\ 6 \times 10^{+7}$	second (s) (mean solar)	
1 year 1900, tropical, Jan., day 0, hour 12	=	$3.155\ 692\ 597\ 47 \times 10^{+7}$	second (s) (ephemeris)	
1 year 1900, tropical, Jan., day 0, hour 12	=	$3.155\ 692\ 597\ 47 \times 10^{+7}$	second (s)	

TABLE 5-2
UNIT EQUALITIES—LISTING BY PHYSICAL QUANTITY

ACCELERATION

1 foot/second^2	=	3.048×10^{-1}	metre/second^2 (m/s^2)	*
1 free fall, standard	=	9.806 65	metre/second^2 (m/s^2)	*
1 galileo (Gal)	=	1.00×10^{-2}	metre/second^2 (m/s^2)	*
1 inch/second^2	=	2.540×10^{-2}	metre/second^2	

AREA

1 acre	=	$4.046\ 856\ 422\ 4 \times 10^{+3}$	metre^2 (m^2)	*
1 are	=	$1.00 \times 10^{+2}$	metre^2 (m^2)	*
1 barn	=	1.00×10^{-28}	metre^2 (m^2)	*
1 circular mil	=	$5.067\ 074\ 8 \times 10^{-10}$	metre^2 (m^2)	
1 foot^2	=	$9.290\ 304 \times 10^{-2}$	metre^2 (m^2)	*
1 hectare	=	$1.00 \times 10^{+4}$	metre^2 (m^2)	*
1 inch^2	=	$6.451\ 600 \times 10^{-4}$	metre^2 (m^2)	*
1 mile^2 (U.S. statute)	=	$2.589\ 988 \times 10^{+6}$	metre^2 (m^2)	
1 section	=	$2.589\ 988\ 110\ 336 \times 10^{+6}$	metre^2 (m^2)	*
1 township	=	$9.323\ 957\ 2 \times 10^{+7}$	metre^2 (m^2)	
1 yard^2	=	$8.361\ 274 \times 10^{-1}$	metre^2 (m^2)	

TABLE 5-2 (cont'd)

BENDING MOMENT OR TORQUE

1 dyne-centimetre	=	1.00×10^{-7}	newton-metre (N• m)	*
1 kilogram-force-metre	=	9.806 650	newton-metre (N• m)	*
1 ounce-force-inch	=	$7.061\ 552 \times 10^{-3}$	newton-metre (N• m)	
1 pound-force-inch	=	$1.129\ 848 \times 10^{-1}$	newton-metre (N• m)	
1 pound-force-foot	=	1.355 818	newton-metre (N• m)	

(BENDING MOMENT OR TORQUE)/LENGTH

1 pound-force-foot/inch	=	$5.337\ 866 \times 10^{+1}$	newton-metre/ metre (N• m/m)	
1 pound-force-inch/inch	=	4.448 222	newton-metre/ metre (N• m/m)	

CAPACITY (SEE VOLUME)

DENSITY (SEE MASS/VOLUME)

ELECTRICITY AND MAGNETISM

1 abampere	=	$1.00 \times 10^{+1}$	ampere (A)	*
1 abcoulomb	=	$1.00 \times 10^{+1}$	coulomb (C)	*
1 abfarad	=	$1.00 \times 10^{+9}$	farad (F)	*
1 abhenry	=	1.00×10^{-9}	henry (H)	*
1 abmho	=	$1.00 \times 10^{+9}$	siemens (S)	*
1 abohm	=	1.00×10^{-9}	ohm (Ω)	*

TABLE 5-2 (cont'd)

ELECTRICITY AND MAGNETISM (CONT'D)

abvolt	=	1.00×10^{-8}	volt (V)	*
ampere (International of 1948)	=	$9.998\ 43 \times 10^{-1}$	ampere (A)	
ampere (U.S. legal 1948)	=	1.000 008	ampere (A)	
ampere-hour	=	$3.600 \times 10^{+3}$	coulomb (C)	*
coulomb (International of 1948)	=	$9.998\ 43 \times 10^{-1}$	coulomb (C)	
coulomb (U.S. Legal 1948)	=	1.000 008	coulomb (C)	
EMU of capacitance	=	$1.00 \times 10^{+9}$	farad (F)	*
EMU of current	=	$1.00 \times 10^{+1}$	ampere (A)	*
EMU of electric potential	=	1.00×10^{-8}	volt (V)	*
EMU of inductance	=	1.00×10^{-9}	henry (H)	*
EMU of resistance	=	1.00×10^{-9}	ohm (Ω)	*
ESU of capacitance	=	$1.112\ 650 \times 10^{-12}$	farad (F)	
ESU of current	=	$3.335\ 6 \times 10^{-10}$	ampere (A)	
ESU of electric potential	=	$2.997\ 9 \times 10^{+2}$	volt (V)	
ESU of inductance	=	$8.987\ 554 \times 10^{+11}$	henry (H)	
ESU of resistance	=	$8.987\ 554 \times 10^{+11}$	ohm (Ω)	
farad (International U.S.)	=	$9.995\ 05 \times 10^{-1}$	farad (F)	
faraday (based on carbon-12)	=	$9.648\ 70 \times 10^{+4}$	coulomb (C)	
faraday (chemical)	=	$9.649\ 57 \times 10^{+4}$	coulomb (C)	
faraday (physical)	=	$9.652\ 19 \times 10^{+4}$	coulomb (C)	
gamma (γ)	=	1.00×10^{-9}	tesla (T)	*
gauss (Gs)	=	1.00×10^{-4}	tesla (T)	*
gilbert (Gb)	=	$7.957\ 747\ 2 \times 10^{-1}$	ampere-turn	
henry (international of 1948)	=	1.000 495	henry (H)	

TABLE 5-2 (cont'd)

ELECTRICITY AND MAGNETISM (CONT'D)

1 maxwell	=	1.00×10^{-8}	weber (Wb)	*
1 oersted (Oe)	=	$7.957\ 747\ 2 \times 10^{+1}$	ampere/metre (A/m)	
1 ohm (international of 1948)	=	1.000 495	ohm (Ω)	
1 ohm-centimetre	=	1.00×10^{-2}	ohm-metre (Ω • m)	*
1 statampere	=	$3.335\ 640 \times 10^{-10}$	ampere (A)	
1 statcoulomb	=	$3.335\ 640 \times 10^{-10}$	coulomb (C)	
1 statfarad	=	$1.112\ 650 \times 10^{-12}$	farad (F)	
1 stathenry	=	$8.987\ 554 \times 10^{+11}$	henry (H)	
1 statmho	=	$1.112\ 650 \times 10^{-12}$	siemens (S)	
1 statohm	=	$8.987\ 554 \times 10^{+11}$	ohm (Ω)	
1 statvolt	=	$2.997\ 925 \times 10^{+2}$	volt (V)	
1 unit pole	=	$1.256\ 637 \times 10^{-7}$	weber (Wb)	
1 volt (international of 1948)	=	1.000 338	volt (V)	
1 volt (U.S. legal 1948)	=	1.000 008	volt (V)	

ENERGY

1 British thermal unit (ISO/TC 12)	=	$1.055\ 06 \times 10^{+3}$	joule (J)
1 British thermal unit (International Steam Table)	=	$1.055\ 04 \times 10^{+3}$	joule (J)
1 British thermal unit (mean)	=	$1.055\ 87 \times 10^{+3}$	joule (J)
1 British thermal unit (thermochemical)	=	$1.054\ 350\ 264\ 488 \times 10^{+3}$	joule (J)
1 British thermal unit (39°F)	=	$1.059\ 67 \times 10^{+3}$	joule (J)

TABLE 5-2 (cont'd)

ENERGY (CONT'D)

1 British thermal unit (60°F)	=	$1.054\ 68 \times 10^{+3}$	joule (J)	
1 calorie (International Steam Table)	=	4.1868	joule (J)	
1 calorie (mean)	=	4.190 02	joule (J)	
1 calorie (thermochemical)	=	4.184	joule (J)	*
1 calorie (15°C)	=	4.185 80	joule (J)	
1 calorie (20°C)	=	4.181 90	joule (J)	
1 calorie (kilogram, International Steam Table)	=	$4.1868 \times 10^{+3}$	joule (J)	
1 calorie (kilogram, mean)	=	$4.190\ 02 \times 10^{+3}$	joule (J)	
1 calorie (kilogram, thermochemical)	=	$4.184 \times 10^{+3}$	joule (J)	*
1 electron volt	=	$1.602\ 10 \times 10^{-19}$	joule (J)	
1 erg	=	1.00×10^{-7}	joule (J)	*
1 foot pound-force	=	1.355 817 9	joule (J)	
1 foot poundal	=	$4.214\ 011 \times 10^{-2}$	joule (J)	
1 joule (U.S. legal 1948)	=	1.000 017	joule (J)	
1 joule (international of 1948)	=	1.000 165	joule (J)	
1 kilocalorie (International Steam Table)	=	$4.186\ 74 \times 10^{+3}$	joule (J)	
1 kilocalorie (mean)	=	$4.190\ 02 \times 10^{+3}$	joule (J)	
1 kilocalorie (thermochemical)	=	$4.184 \times 10^{+3}$	joule (J)	*
1 kilowatt hour		$3.600 \times 10^{+6}$	joule (J)	*
1 kilowatt hour (U.S. legal 1948)	=	$3.600\ 061 \times 10^{+6}$	joule (J)	
1 kilowatt hour (international U.S.)	=	$3.600\ 655 \times 10^{+6}$	joule (J)	

TABLE 5-2 (cont'd)

ENERGY (CONT'D)

1 ton (nuclear equivalent of TNT)	=	$4.20 \times 10^{+9}$	joule (J)
1 watt-hour	=	$3.600 \times 10^{+3}$	joule (J)
1 watt-second	=	1.00	joule (J)

ENERGY/AREA TIME

1 Btu (thermochemical)/(foot^2-second)	=	$1.134\ 893\ 1 \times 10^{+4}$	watt/metre^2 (W/m^2)
1 Btu (thermochemical)/(foot^2-minute)	=	$1.891\ 488\ 5 \times 10^{+2}$	watt/metre^2 (W/m^2)
1 Btu (thermochemical)/(foot^2-hour)	=	3.152 480 8	watt/metre^2 (W/m^2)
1 Btu (thermochemical)/(inch^2-second)	=	$1.634\ 246\ 2 \times 10^{+6}$	watt/metre^2 (W/m^2)
1 calorie (thermochemical)/(centimetre^2-minute)	=	$6.973\ 333\ 3 \times 10^{+2}$	watt/metre^2 (W/m^2)
1 erg/(centimetre^2-second)	=	1.00×10^{-3}	watt/metre^2 (W/m^2)
1 watt/centimetre^2	=	$1.00 \times 10^{+4}$	watt/metre^2 (W/m^2)

FLOW (SEE MASS/TIME OR VOLUME/TIME)

FORCE

1 dyne	=	1.00×10^{-5}	newton (N)
1 kilogram force (kgf)	=	9.806 650	newton (N)
1 kip (1000 lbf)	=	$4.448\ 221\ 615\ 260\ 5 \times 10^{+3}$	newton (N)

TABLE 5-2 (cont'd)

FORCE (CONT'D)

				*
1 ounce-force (avoirdupois)	=	$2.780\ 138\ 5 \times 10^{-1}$	newton (N)	
1 pound force, lbf (avoirdupois)	=	4.448 221 615 260 5	newton (N)	*
1 poundal	=	$1.382\ 549\ 543\ 76 \times 10^{-1}$	newton (N)	*

FORCE/AREA (SEE PRESSURE)

FORCE/LENGTH

1 pound-force/inch	=	$1.751\ 268 \times 10^{+2}$	newton/metre (N/m)
1 pound-force/foot	=	$1.459\ 390 \times 10^{+1}$	newton/metre (N/m)

HEAT

1 Btu (thermochemical)-inch/(second-foot^2-°F) (k, thermal conductivity)	=	$5.188\ 732 \times 10^{+2}$	watt/(metre-kelvin) (W/m • K)
1 Btu (International Table)-inch/(second-foot^2-°F) (k, thermal conductivity)	=	$5.192\ 204 \times 10^{+2}$	watt/(metre-kelvin) (W/m • K)
1 Btu (thermochemical)-inch/(hour-foot^2-°F) (k, thermal conductivity)	=	$1.441\ 314 \times 10^{-1}$	watt/(metre-kelvin) (W/m • K)
1 Btu (International Table)-inch/(hour-foot^2-°F) (k, thermal conductivity)	=	$1.442\ 279 \times 10^{-1}$	watt/(metre-kelvin) (W/m • K)

TABLE 5-2 (cont'd)

HEAT (CONT'D)

1 Btu (International Table)/foot^2	=	$1.135\ 653 \times 10^{+4}$	joule/metre^2 (J/m^2)	
1 Btu (thermochemical)/foot^2	=	$1.134\ 893 \times 10^{+4}$	joule/metre^2 (J/m^2)	
1 Btu (International Table)/(hour-foot^2-°F) (C, thermal conductance)	=	5.678 263	watt/(metre^2-kelvin) (W/m^2 • K)	
1 Btu (thermochemical)/(hour-foot^2-°F) (C, thermal conductance)	=	5.674 466	watt/(metre^2-kelvin) (W/m^2 • K)	
1 Btu (International Table)/pound-mass	=	$2.326 \times 10^{+3}$	joule/kilogram (J/kg)	*
1 Btu (thermochemical)/pound-mass	=	$2.324\ 444 \times 10^{+3}$	joule/kilogram (J/kg)	
1 Btu (International Table)/(pound mass-°F) (c, heat capacity)	=	$4.186\ 800 \times 10^{+3}$	joule/(kilogram -kelvin) (J/kg • K)	*
1 Btu (thermochemical)/(pound mass-°F) (c, heat capacity)	=	$4.184\ 000 \times 10^{+3}$	joule/(kilogram -kelvin) (J/kg • K)	
1 Btu (International Table)/(second-foot^2-°F)	=	$2.044\ 175 \times 10^{+4}$	watt/(metre^2-kelvin) (W/m^2 • K)	
1 Btu (thermochemical)/(second-foot^2-°F)	=	$2.042\ 808 \times 10^{+4}$	watt/(metre^2-kelvin) (W/m^2 • K)	
1 cal (thermochemical)/centimetre^2	=	$4.184 \times 10^{+4}$	joule/metre^2 (J/m^2)	*
1 cal (thermochemical)/(centimetre^2-second)	=	$4.184 \times 10^{+4}$	watt/metre^2 (W/m^2)	*
1 cal (thermochemical)/(centimetre-second-°C)	=	$4.184 \times 10^{+2}$	watt/(metre-kelvin) (W/m • K)	*
1 cal (International Table)/gram	=	$4.186\ 800 \times 10^{+3}$	joule/kilogram (J/kg)	*
1 cal (International Table)/(gram-°C)	=	$4.186\ 800 \times 10^{+3}$	joule/(kilogram -kelvin) (J/kg • K)	*

TABLE 5-2 (cont'd)

HEAT (CONT'D)

1 cal (thermochemical)/gram	=	$4.184 \times 10^{+3}$	joule/kilogram (J/kg)	*
1 cal (thermochemical)/(gram-°C)	=	$4.184 \times 10^{+3}$	joule/(kilogram kelvin) (J/kg • K)	*
1 clo	=	$2.003\ 712 \times 10^{-1}$	kelvin-metre^2/watt (K • m^2/W)	
1 deg F • h • ft^2/Btu (thermochemical) (R, thermal resistance)	=	$1.762\ 280 \times 10^{-1}$	kelvin-metre^2/watt (K • m^2/W)	
1 deg F • h • ft^2/Btu (International Table) (R, thermal resistance)	=	$1.761\ 102 \times 10^{-1}$	kelvin-metre^2/watt (K • m^2/W)	
1 ft^2/h (thermal diffusivity)	=	$2.580\ 640 \times 10^{-5}$	metre^2/second (m^2/s)	*

LENGTH

1 angstrom	=	1.00×10^{-10}	metre (m)	*
1 astronomical unit (AU)	=	$1.495\ 978\ 9 \times 10^{+11}$	metre (m)	
1 cable	=	$2.194\ 56 \times 10^{+2}$	metre (m)	*
1 caliber	=	2.54×10^{-4}	metre (m)	*
1 chain (surveyor or gunter)	=	$2.011\ 68 \times 10^{+1}$	metre (m)	*
1 chain (engineer or ramden)	=	$3.048 \times 10^{+1}$	metre (m)	*
1 cubit	=	4.572×10^{-1}	metre (m)	*
1 fathom	=	1.8288	metre (m)	*
1 fermi (femtometre)	=	1.00×10^{-15}	metre (m)	*
1 foot	=	3.048×10^{-1}	metre (m)	*

TABLE 5-2 (cont'd)

LENGTH (CONT'D)

1 foot (U.S. survey)	=	$3.048\ 006\ 096 \times 10^{-1}$	metre (m)	
1 furlong	=	$2.011\ 68 \times 10^{+2}$	metre (m)	*
1 hand	=	1.016×10^{-1}	metre (m)	*
1 inch	=	2.54×10^{-2}	metre (m)	*
1 league (U.K. nautical)	=	$5.559\ 552 \times 10^{+3}$	metre (m)	*
1 league (international nautical)	=	$5.556 \times 10^{+3}$	metre (m)	*
1 league (statute)	=	$4.828\ 032 \times 10^{+3}$	metre (m)	*
1 light year	=	$9.460\ 55 \times 10^{+15}$	metre (m)	
1 link (engineer or ramden)	=	3.048×10^{-1}	metre (m)	*
1 link (surveyor or gunter)	=	$2.011\ 68 \times 10^{-1}$	metre (m)	*
1 metre (m)	=	$1.650\ 763\ 73 \times 10^{+6}$	wavelengths Kr 86[a]	*
1 microinch	=	2.540×10^{-8}	metre (m)	*
1 micron	=	1.00×10^{-6}	metre (m)	*
1 mil	=	2.54×10^{-5}	metre (m)	*
1 mile (U.S. statute)	=	$1.609\ 344 \times 10^{+3}$	metre (m)	*
1 mile (U.K. nautical)	=	$1.853\ 184 \times 10^{+3}$	metre (m)	*
1 mile (international nautical)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 mile (U.S. nautical)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 nautical mile (U.K.)	=	$1.853\ 184 \times 10^{+3}$	metre (m)	*
1 nautical mile (international)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 nautical mile (U.S.)	=	$1.852 \times 10^{+3}$	metre (m)	*
1 pace	=	7.62×10^{-1}	metre (m)	*
1 parsec	=	$3.083\ 74 \times 10^{+16}$	metre (m)	

[a]See par. 2-2.2.

TABLE 5-2 (cont'd)

LENGTH (CONT'D)

1 perch	=	5.0292	metre (m)	*
1 pica (printer's)	=	$4.217\ 517\ 6 \times 10^{-3}$	metre (m)	*
1 point (printer's)	=	$3.514\ 598 \times 10^{-4}$	metre (m)	*
1 pole	=	5.0292	metre (m)	*
1 rod	=	5.0292	metre (m)	*
1 skein	=	$1.097\ 28 \times 10^{+2}$	metre (m)	*
1 span	=	2.286×10^{-1}	metre (m)	*
1 statute mile (U.S.)	=	$1.609\ 344 \times 10^{+3}$	metre (m)	*
1 yard	=	$9.144\ 000 \times 10^{-1}$	metre (m)	*

LIGHT

1 footcandle	=	$1.076\ 391 \times 10^{+1}$	lumen/metre^2 (lm/m^2)	
1 footcandle	=	$1.076\ 391 \times 10^{+1}$	lux (lx)	
1 footlambert	=	3.426 259	candela/metre^2 (cd/m^2)	
1 lux	=	1.00	lumen/metre^2 (lm/m^2)	*

MASS

1 carat	=	2.00×10^{-4}	kilogram (kg)	*
1 dram (avoirdupois)	=	$1.771\ 845\ 195\ 312\ 5 \times 10^{-3}$	kilogram (kg)	*
1 dram (troy or apothecary)	=	$3.887\ 934\ 6 \times 10^{-3}$	kilogram (kg)	*
1 grain	=	$6.479\ 891 \times 10^{-5}$	kilogram (kg)	*
1 gram	=	1.00×10^{-3}	kilogram (kg)	*

TABLE 5-2 (cont'd)

MASS (CONT'D)

1 hundredweight (long)	=	$5.080\ 234\ 544 \times 10^{+1}$	kilogram (kg)	*
1 hundredweight (short)	=	$4.535\ 923\ 7 \times 10^{+1}$	kilogram (kg)	*
1 kilogram-force-second^2/metre (mass)	=	9.806 650	kilogram (kg)	*
1 kilogram mass	=	1.00	kilogram (kg)	*
1 ounce-mass (avoirdupois)	=	$2.834\ 952\ 312\ 5 \times 10^{-2}$	kilogram (kg)	*
1 ounce-mass (troy or apothecary)	=	$3.110\ 347\ 68 \times 10^{-2}$	kilogram (kg)	*
1 pennyweight	=	$1.555\ 173\ 84 \times 10^{-3}$	kilogram (kg)	*
1 pound-mass (lbm avoirdupois)	=	$4.535\ 923\ 7 \times 10^{-1}$	kilogram (kg)	*
1 pound-mass (troy or apothecary)	=	$3.732\ 417\ 216 \times 10^{-1}$	kilogram (kg)	*
1 scruple (apothecary)	=	$1.295\ 978\ 2 \times 10^{-3}$	kilogram (kg)	*
1 slug	=	$1.459\ 390\ 29 \times 10^{+1}$	kilogram (kg)	
1 ton (assay)	=	$2.916\ 666\ 6 \times 10^{-2}$	kilogram (kg)	
1 ton (long 2240 lbm)	=	$1.016\ 046\ 908\ 8 \times 10^{+3}$	kilogram (kg)	*
1 ton (metric)	=	$1.00 \times 10^{+3}$	kilogram (kg)	*
1 ton (short, 2000 lbm)	=	$9.071\ 847\ 4 \times 10^{+2}$	kilogram (kg)	*
1 tonne	=	$1.00 \times 10^{+3}$	kilogram (kg)	*

MASS/AREA

1 ounce-mass/yard^2	=	$3.390\ 575 \times 10^{-2}$	kilogram/metre^2 (kg/m^2)
1 pound-mass/foot^2	=	4.882 428	kilogram/metre^2 (kg/m^2)

TABLE 5-2 (cont'd)

MASS/CAPACITY (SEE MASS/VOLUME)

MASS/TIME (INCLUDES FLOW)

1 perm (0 °C)	=	$5.721\ 35 \times 10^{-11}$	kilogram/(pascal-second-metre^2) (kg/(Pa • s • m^2))
1 perm (23 °C)	=	$5.745\ 25 \times 10^{-11}$	kilogram/(pascal-second-metre^2) (kg/(Pa • s • m^2))
1 perm-inch (0 °C)	=	$1.453\ 22 \times 10^{-12}$	kilogram/(pascal-second-metre) (kg/(Pa • s • m))
1 perm-inch (23 °C)	=	$1.459\ 29 \times 10^{-12}$	kilogram/(pascal-second-metre) (kg/(Pa • s • m))
1 pound-mass/second	=	$4.535\ 924 \times 10^{-1}$	kilogram/second (kg/s)
1 pound-mass/minute	=	$7.559\ 873 \times 10^{-3}$	kilogram/second (kg/s)
1 ton (short, mass)/hour	=	$2.519\ 958 \times 10^{-1}$	kilogram/second (kg/s)

MASS/VOLUME (INCLUDES DENSITY AND MASS CAPACITY)

1 grain (lbm avoirdupois/7000)/gallon (U.S. liquid)	=	$1.711\ 806 \times 10^{-2}$	kilogram/metre^3 (kg/m^3)
1 gram/centimetre^3	=	$1.00 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)
1 ounce (avoirdupois)/gallon (U.K. liquid)	=	6.236 027	kilogram/metre^3 (kg/m^3)
1 ounce (avoirdupois)/gallon (U.S. liquid)	=	7.489 152	kilogram/metre^3 (kg/m^3)
1 ounce (avoirdupois) (mass)/inch^3	=	$1.729\ 994 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)
1 pound-mass/foot^3	=	$1.601\ 846 \times 10^{+1}$	kilogram/metre^3 (kg/m^3)

TABLE 5-2 (cont'd)

MASS/VOLUME (INCLUDES DENSITY AND MASS CAPACITY)(CONT'D)

1 pound-mass/inch^3	=	$2.767\ 990 \times 10^{+4}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/gallon (U.K. liquid)	=	$9.977\ 644 \times 10^{+1}$	kilogram/metre^3 (kg/m^3)	
1 pound-mass/gallon (U.S. liquid)	=	$1.198\ 264 \times 10^{+2}$	kilogram/metre^3 (kg/m^3)	
1 slug/foot^3	=	$5.153\ 788 \times 10^{+2}$	kilogram/metre^3 (kg/m^3)	
1 ton (long, mass)/yard^3	=	$1.328\ 939 \times 10^{+3}$	kilogram/metre^3 (kg/m^3)	

POWER

1 Btu (International Table)/hour	=	$2.930\ 711 \times 10^{-1}$	watt (W)	
1 Btu (thermochemical)/second	=	$1.054\ 350 \times 10^{+3}$	watt (W)	
1 Btu (thermochemical)/minute	=	$1.757\ 250 \times 10^{+1}$	watt (W)	
1 Btu (thermochemical)/hour	=	$2.928\ 751 \times 10^{-1}$	watt (W)	
1 cal (thermochemical)/second	=	4.184	watt (W)	*
1 cal (thermochemical)/minute	=	$6.973\ 333 \times 10^{-2}$	watt (W)	
1 erg/second	=	1.00×10^{-7}	watt (W)	*
1 foot-pound-force/hour	=	$3.766\ 161 \times 10^{-4}$	watt (W)	
1 foot-pound-force/minute	=	$2.259\ 697 \times 10^{-2}$	watt (W)	
1 foot-pound-force/second	=	1.355 818	watt (W)	
1 horsepower (550 ft • lbf/s)	=	$7.456\ 998\ 7 \times 10^{+2}$	watt (W)	
1 horsepower (boiler)	=	$9.809\ 50 \times 10^{+3}$	watt (W)	

TABLE 5-2 (cont'd)

POWER (CONT'D)

1 horsepower (electric)	=	$7.46 \times 10^{+2}$	watt (W)	*
1 horsepower (metric)	=	$7.354\ 99 \times 10^{+2}$	watt (W)	
1 horsepower (water)	=	$7.460\ 43 \times 10^{+2}$	watt (W)	
1 horsepower (U.K.)	=	$7.457 \times 10^{+2}$	watt (W)	
1 kilocalorie (thermochemical)/ minute	=	$6.973\ 333 \times 10^{+1}$	watt (W)	
1 kilocalorie (thermochemical)/ second	=	$4.184 \times 10^{+3}$	watt (W)	*
1 watt (international of 1948)	=	1.000 165	watt (W)	
1 watt (U.S. legal 1948)	=	1.000 017	watt (W)	

PRESSURE OR STRESS (FORCE/AREA)

1 atmosphere (normal = 760 torr)	=	$1.013\ 25 \times 10^{+5}$	pascal (Pa)	
1 atmosphere (technical = 1 kgf/cm^2)	=	$9.806\ 650 \times 10^{+4}$	pascal (Pa)	*
1 bar	=	$1.00 \times 10^{+5}$	pascal (Pa)	*
1 barye	=	1.00×10^{-1}	pascal (Pa)	*
1 centimetre of mercury (0 °C)	=	$1.333\ 22 \times 10^{+3}$	pascal (Pa)	
1 centimetre of water (4 °C)	=	$9.806\ 38 \times 10^{+1}$	pascal (Pa)	
1 decibar	=	$1.00 \times 10^{+4}$	pascal (Pa)	*
1 dyne per centimetre^2	=	1.00×10^{-1}	pascal (Pa)	*
1 foot of water (39.2 °F)	=	$2.988\ 98 \times 10^{+3}$	pascal (Pa)	
1 gram-force/centimetre^2	=	$9.806\ 650 \times 10^{+1}$	pascal (Pa)	*
1 inch of mercury (32 °F)	=	$3.386\ 389 \times 10^{+3}$	pascal (Pa)	

TABLE 5-2 (cont'd)

PRESSURE OR STRESS (FORCE/AREA) (CONT'D)

1 inch of mercury (60 °F)	=	$3.376\ 85 \times 10^{+3}$	pascal (Pa)	
1 inch of water (39.2 °F)	=	$2.490\ 82 \times 10^{+2}$	pascal (Pa)	
1 inch of water (60 °F)	=	$2.488\ 4 \times 10^{+2}$	pascal (Pa)	
1 kilogram-force/centimetre^2	=	$9.806\ 650 \times 10^{+4}$	pascal (Pa)	*
1 kilogram-force/metre^2	=	9.806 650	pascal (Pa)	*
1 kilogram-force/millimetre^2	=	$9.806\ 650 \times 10^{+6}$	pascal (Pa)	*
1 kip/inch^2 (ksi)	=	$6.894\ 757 \times 10^{+6}$	pascal (Pa)	
1 millibar	=	$1.00 \times 10^{+2}$	pascal (Pa)	*
1 millimetre of mercury (0 °C)	=	$1.333\ 224 \times 10^{+2}$	pascal (Pa)	
1 poundal/foot^2	=	1.488 164	pascal (Pa)	
1 pound-force/foot^2	=	$4.788\ 026 \times 10^{+1}$	pascal (Pa)	
1 pound-force/inch^2 (psi)	=	$6.894\ 757 \times 10^{+3}$	pascal (Pa)	
1 psi	=	$6.894\ 757 \times 10^{+3}$	pascal (Pa)	
1 torr (mm Hg, 0°C)	=	$1.333\ 22 \times 10^{+2}$	pascal (Pa)	

SPEED (SEE VELOCITY)

STRESS (SEE PRESSURE)

TEMPERATURE

degree (Celsius)	$T(\text{K}) = t(°\text{C}) + 273.15$	kelvin (K)	*
degree Fahrenheit	$T(\text{K}) = (t_F + 459.67)/1.8$	kelvin (K)	
degree Rankine	$T(\text{K}) = t_R/1.8$	kelvin (K)	
degree Fahrenheit	$t(°\text{C}) = (t_F - 32)/1.8$	degree Celsius	
kelvin	$t(°\text{C}) = t(\text{K}) - 273.15$	degree Celsius	

TABLE 5-2 (cont'd)

TIME

1 day (mean solar)	=	$8.64 \times 10^{+4}$	second (mean solar)	*
1 day (sidereal)	=	$8.616\ 409\ 0 \times 10^{+4}$	second (mean solar)	
1 hour (mean solar)	=	$3.60 \times 10^{+3}$	second (mean solar)	*
1 hour (sidereal)	=	$3.590\ 170\ 4 \times 10^{+3}$	second (mean solar)	
1 minute (mean solar)	=	$6.00 \times 10^{+1}$	second (mean solar)	*
1 minute (sidereal)	=	$5.983\ 617\ 4 \times 10^{+1}$	second (mean solar)	
1 month (mean calendar)	=	$2.628 \times 10^{+6}$	second (mean solar)	*
1 second (ephemeris)	=	1.000 000 000	second	
1 second (mean solar)	=	Consult American Ephemeris and Nautical Almanac	second (ephemeris)	
1 second (sidereal)	=	$9.972\ 695\ 7 \times 10^{-1}$	second (mean solar)	
1 year (calendar)	=	$3.1536 \times 10^{+7}$	second (mean solar)	*
1 year (sidereal)	=	$3.155\ 815\ 0 \times 10^{+7}$	second (mean solar)	
1 year (tropical)	=	$3.155\ 692\ 6 \times 10^{+7}$	second (mean solar)	
1 year 1900, tropical, Jan., day 0, hour 12	=	$3.155\ 692\ 597\ 47 \times 10^{+7}$	second (ephemeris)	*
1 year 1900, tropical, Jan., day 0, hour 12	=	$3.155\ 692\ 597\ 47 \times 10^{+7}$	second	

TORQUE (SEE BENDING MOMENT)

TABLE 5-2 (cont'd)

VELOCITY/SPEED

1 foot/hour	=	$8.466\ 667 \times 10^{-5}$	metre/second (m/s)	
1 foot/minute	=	5.080×10^{-3}	metre/second (m/s)	*
1 foot/second	=	3.048×10^{-1}	metre/second (m/s)	*
1 inch/second	=	2.540×10^{-2}	metre/second (m/s)	*
1 kilometre/hour	=	$2.777\ 778 \times 10^{-1}$	metre/second (m/s)	
1 knot (international)	=	$5.144\ 444\ 444 \times 10^{-1}$	metre/second (m/s)	
1 mile/hour (U.S. statute)	=	4.4704×10^{-1}	metre/second (m/s)	*
1 mile/hour (U.S. statute)	=	1.609 344	kilometre/hour (km/hr)	*
1 mile/minute (U.S. statute)	=	$2.682\ 240 \times 10^{+1}$	metre/second (m/s)	*
1 mile/second (U.S. statute)	=	$1.609\ 344 \times 10^{+3}$	metre/second (m/s)	*

VISCOSITY

1 centipoise	=	1.00×10^{-3}	pascal-second (Pa • s)	*
1 centistoke	=	1.00×10^{-6}	metre^2/second (m^2/s)	*
1 foot^2/second	=	$9.290\ 304 \times 10^{-2}$	metre^2/second (m^2/s)	*
1 poise	=	1.00×10^{-1}	pascal-second (Pa • s)	
1 pound-force-second/foot^2	=	$4.788\ 025\ 8 \times 10^{+1}$	pascal-second (Pa • s)	
1 pound-mass/(foot-second)	=	1.488 163 9	pascal-second (Pa • s)	*
1 poundal-second/foot^2	=	1.488 163 9	pascal-second (Pa • s)	

TABLE 5-2 (cont'd)

VISCOSITY (CONT'D)

1 rhe	=	$1.00 \times 10^{+1}$	1/(pascal-second) (1/(Pa • s))	*
1 slug/(foot-second)	=	$4.788\ 025\ 8 \times 10^{+1}$	pascal-second (Pa • s)	
1 stoke	=	1.00×10^{-4}	metre^2/second (m^2/s)	*

VOLUME

1 acre-foot	=	$1.233\ 481\ 9 \times 10^{+3}$	metre^3 (m^3)	
1 barrel (petroleum, 42 gallons)	=	$1.589\ 873 \times 10^{-1}$	metre^3 (m^3)	
1 board foot	=	$2.359\ 737\ 216 \times 10^{-3}$	metre^3 (m^3)	*
1 bushel (U.S.)	=	$3.523\ 907\ 016\ 688 \times 10^{-2}$	metre^3 (m^3)	*
1 cord	=	$3.624\ 556\ 3$	metre^3 (m^3)	
1 cup	=	$2.365\ 882\ 365 \times 10^{-4}$	metre^3 (m^3)	*
1 dram (U.S. fluid)	=	$3.696\ 691\ 195\ 312\ 5 \times 10^{-6}$	metre^3 (m^3)	*
1 fluid ounce (U.S.)	=	$2.957\ 352\ 956\ 25 \times 10^{-5}$	metre^3 (m^3)	*
1 foot^3	=	$2.831\ 684\ 659\ 2 \times 10^{-2}$	metre^3 (m^3)	*
1 gallon (U.K. liquid)	=	$4.546\ 087 \times 10^{-3}$	metre^3 (m^3)	
1 gallon (U.S. dry)	=	$4.404\ 883\ 770\ 86 \times 10^{-3}$	metre^3 (m^3)	*
1 gallon (U.S. liquid)	=	$3.785\ 411\ 784 \times 10^{-3}$	metre^3 (m^3)	*
1 gill (U.K.)	=	$1.420\ 652 \times 10^{-4}$	metre^3 (m^3)	
1 gill (U.S.)	=	$1.182\ 941\ 2 \times 10^{-4}$	metre^3 (m^3)	
1 hogshead (U.S.)	=	$2.384\ 809\ 423\ 92 \times 10^{-1}$	metre^3 (m^3)	*
1 inch^3	=	$1.638\ 706\ 4 \times 10^{-5}$	metre^3 (m^3)	*

TABLE 5-2 (cont'd)

VOLUME (CONT'D)

1 litre	=	1.00×10^{-3}	metre^3 (m^3)	*
1 ounce (U.S. fluid)	=	$2.957\ 352\ 956\ 25 \times 10^{-5}$	metre^3 (m^3)	*
1 peck (U.S.)	=	$8.809\ 767\ 541\ 72 \times 10^{-3}$	metre^3 (m^3)	*
1 pint (U.S. dry)	=	$5.506\ 104\ 713\ 575 \times 10^{-4}$	metre^3 (m^3)	*
1 pint (U.S. liquid)	=	$4.731\ 764\ 73 \times 10^{-4}$	metre^3 (m^3)	*
1 quart (U.S. dry)	=	$1.101\ 220\ 942\ 715 \times 10^{-3}$	metre^3 (m^3)	*
1 quart (U.S. liquid)	=	$9.463\ 529\ 5 \times 10^{-4}$	metre^3 (m^3)	
1 stere	=	1.00	metre^3 (m^3)	*
1 tablespoon	=	$1.478\ 676\ 478\ 125 \times 10^{-5}$	metre^3 (m^3)	*
1 teaspoon	=	$4.928\ 921\ 593\ 75 \times 10^{-6}$	metre^3 (m^3)	*
1 ton (register)	=	2.831 684 659 2	metre^3 (m^3)	*
1 yard^3	=	$7.645\ 548\ 579\ 84 \times 10^{-1}$	metre^3 (m^3)	*

VOLUME/TIME (INCLUDES FLOW)

1 foot^3/minute	=	$4.719\ 474 \times 10^{-4}$	metre^3/second (m^3/s)
1 foot^3/second	=	$2.831\ 685 \times 10^{-2}$	metre^3/second (m^3/s)
1 gallon (U.S. liquid)/day	=	$4.381\ 246 \times 10^{-8}$	metre^3/second (m^3/s)
1 gallon (U.S. liquid)/minute	=	$6.309\ 020 \times 10^{-5}$	metre^3/second (m^3/s)
1 inch^3/minute	=	$2.731\ 177 \times 10^{-7}$	metre^3/second (m^3/s)
1 yard^3/minute	=	$1.274\ 258 \times 10^{-2}$	metre^3/second (m^3/s)

WORK (SEE ENERGY)

TABLE 5-3
EXPERIMENTALLY DETERMINED CONSTANTS

Avogadro constant, N_A	=	$6.022\ 169 \times 10^{26}$ kmole^{-1}
Bohr magneton, μ_B	=	$9.274\ 096 \times 10^{-24}$ J/T
Bohr radius, α_o	=	$5.291\ 771\ 5 \times 10^{-11}$ m
Boltzmann constant, k	=	$1.380\ 622 \times 10^{-23}$ J/K
Classical electron radius, r_e	=	$2.817\ 939 \times 10^{-15}$ m
Compton wavelength of electron, λ_C	=	$2.426\ 309\ 6 \times 10^{-12}$ m
$\lambda_C/(2\pi)$	=	$3.861\ 592 \times 10^{-13}$ m
Compton wavelength of neutron, $\lambda_{C,n}$	=	$1.319\ 621\ 7 \times 10^{-15}$ m
$\lambda_{C,n}/(2\pi)$	=	$2.100\ 243 \times 10^{-16}$ m
Compton wavelength of proton, $\lambda_{C,p}$	=	$1.321\ 440\ 9 \times 10^{-15}$ m
$\lambda_{C,p}/(2\pi)$	=	$2.103\ 139 \times 10^{-16}$ m
Electron charge, e	=	$1.602\ 191\ 7 \times 10^{-19}$ C
Electron charge to mass ratio, e/m_e	=	$1.758\ 802\ 8 \times 10^{11}$ C/kg
Electron magnetic moment, μ_e	=	$9.284\ 851 \times 10^{-24}$ J/G
Electron rest mass, m_e	=	$9.109\ 558 \times 10^{-31}$ kg
	=	$5.485\ 930 \times 10^{-4}$ u

TABLE 5-3 (cont'd)

Faraday constant, F	=	$9.648\ 670 \times 10^{7}$ C/kmole
Fine structure constant, α	=	$7.297\ 351 \times 10^{-3}$
α^{-1}	=	$1.370\ 360\ 2 \times 10^{+2}$
First radiation constant, $8\pi\ hc$	=	$4.992\ 579 \times 10^{-24}$ J • m
Gas constant, R	=	$8.314\ 34 \times 10^{3}$ J/(kmole • K)
Gravitational constant, G	=	$6.673\ 2 \times 10^{-11}$ N • m^2/kg^2
Gyromagnetic ratio of protons in H_2O, γ'_p	=	$2.675\ 127\ 0 \times 10^{8}$ rad/(s • T)
$\gamma'p/(2\pi)$	=	$4.257\ 597 \times 10^{7}$ Hz/T
Gyromagnetic ratio of protons in H_2O, γ_p	=	$2.675\ 196\ 5 \times 10^{8}$ rad/(s • T)
corrected for diamagnetism of H_2O, $\gamma p/(2\pi)$	=	$4.257\ 707 \times 10^{7}$ Hz/T
Magnetic flux quantum, Φ_o	=	$2.067\ 853\ 8 \times 10^{-15}$ Wb
Neutron rest mass, m_n	=	$1.674\ 920 \times 10^{-27}$ kg
	=	1.008 665 20 u
Nuclear magneton, μ_n	=	$5.050\ 951 \times 10^{-27}$ J/T
Planck constant, h	=	$6.626\ 196 \times 10^{-34}$ J • s
$h/(2\pi)$	=	$1.054\ 591\ 9 \times 10^{-34}$ J • s
Proton magnetic moment, μ_p	=	$1.410\ 620\ 3 \times 10^{-26}$ J/T

TABLE 5-3 (cont'd)

Proton rest mass, m_p	=	$1.672\ 614 \times 10^{-27}$ kg
	=	$1.007\ 276\ 61$ u
Quantum of circulation, $h/(2m_e)$	=	$3.636\ 947 \times 10^{-4}$ J • s/kg
h/m_e	=	$7.273\ 894 \times 10^{-4}$ J • s/kg
Rydberg constant, R_∞	=	$1.097\ 373\ 12 \times 10^{7}$ m^{-1}
Second radiation constant, hc/k	=	$1.438\ 833 \times 10^{-2}$ m • K
Speed of light in vacuum, c	=	$2.997\ 925\ 0 \times 10^{8}$ m/s
Stefan-Boltzmann constant, σ	=	$5.669\ 61 \times 10^{-8}$ W • K^4/m^2
Unified atomic mass unit, u	=	$1.660\ 531 \times 10^{-27}$ kg
Volume of ideal gas, standard conditions, V_0	=	$2.241\ 36 \times 10^{1}$ m^3/kmole

TABLE 5-4
DIMENSIONLESS CONSTANTS

eV/Hz	=	$2.417\ 965\ 9 \times 10^{14}$
eV/J	=	$1.602\ 191\ 7 \times 10^{-19}$
eV/K	=	$1.160\ 485 \times 10^{4}$
$eV \bullet m$	=	$8.065\ 456 \times 10^{5}$
$(eV \bullet m)^{-1}$	=	$1.239\ 854\ 1 \times 10^{-6}$
kg/eV	=	$5.609\ 538 \times 10^{35}$
m_e/eV	=	$5.110\ 041 \times 10^{5}$
m_n/eV	=	$9.395\ 527 \times 10^{8}$
m_p/eV	=	$9.382\ 592 \times 10^{8}$
m_p/m_e	=	$1.836\ 109 \times 10^{3}$
R_∞/eV	=	$1.360\ 582\ 6 \times 10^{1}$
R_∞/Hz	=	$3.289\ 842\ 3 \times 10^{15}$
R_∞/J	=	$2.179\ 914 \times 10^{-18}$
R_∞/K	=	$1.578\ 936 \times 10^{5}$
u/eV	=	$9.314\ 812 \times 10^{8}$
u/kg	=	$1.660\ 531 \times 10^{-27}$
μ_e/μ_B	=	$1.001\ 159\ 638\ 9$
μ_p/μ_B	=	$1.521\ 032\ 64 \times 10^{-3}$
μ_p/μ_n	=	$2.792\ 782$
μ'_p/μ_B	=	$1.520\ 993\ 12 \times 10^{-3}$
μ'_p/μ_n	=	$2.792\ 709$

CHAPTER 6
METRICATION OF ENGINEERING DRAWINGS

This chapter describes the use of SI units in military engineering drawings. Practices related to the use of SI units in engineering drawings and dual dimensional engineering drawings are specified in American National Standard, ANSI Y14.5-1973 (Ref. 1), which has been approved for use by the Department of Defense. Where these practices differ from practices applicable to engineering drawings using U.S. customary units they are covered in this handbook.

Par. 6-1 specifically relates to formats of numerical values of dimensions expressed is SI units. Par. 6-2 presents methods of converting the units of toleranced dimensions. Tables for conversion of dimensions in inches, expressed either as common fractions or decimal fractions, are included. Par. 6-3 presents practices to be applied in drawings using SI units and dual dimensional drawings.

6-1 NUMERICAL VALUES OF SI DIMESIONS

The approved method for writing numerical values of SI dimensions in U.S. military engineering drawings is different both from that presented in par. 3-4 of this handbook for physical quantities and from that for engineering drawing dimensions in U.S. customary units (Ref. 1). These differences are delineated in the paragraphs that follow.

A zero is used preceding the decimal point in the numerical value of an SI dimension of less than unity. Examples are:

0.012 mm   0.932 mm

This is inconsistent with the practice of not using the zero when dimensions are expressed in customary units such as:

.832 in.   .005 in.

A decimal point is not used with whole numbers in SI dimesions; it is with dimensions in customary units. Examples of correct expressions in both systems are:

10 mm   381 mm
1290. in   15. in.

Commas are not used to indicate thousands in the values of either SI or U.S. customary dimensions. Additionally, in SI dimensions, a space is *not* used to separate digits into groups of three to the left or right of the decimal point. Examples of correct usuage are:

12368 mm   12.29737 mm
0.0012 mm

It is critical that commas *not* be used because of the European practice of using the comma in place of the decimal point.

In cases where unilateral tolerancing is used (i.e., either the plus or minus tolerance is zero and the other tolerance is nonzero), a single zero is used. This is illustrated by the examples:

$$29\,{}^{\;0}_{-0.02}\ \text{mm} \qquad 39.06\,{}^{+0.005}_{\;0}\ \text{mm}$$

In the case of bilateral tolerancing, zeros should be used such that the number of decimal places in both tolerances are the same. Examples are:

$$15\,{}^{+0.025}_{-0.100}\ \text{mm} \qquad 39.06\,{}^{+0.005}_{-0.010}\ \text{mm}$$

In the usual situation where equal plus and minus tolerances apply, the millimetre dimension and its tolerance do not have to have the same number of decimal places. For example, note the following:

$$32 \pm 0.010 \text{ mm} \qquad 31.96 \pm 0.012 \text{ mm}$$

Where limit dimensioning is used in a drawing and either the maximum or the minimum value is a decimal fraction, zeros should be added to the other limit for uniformity. This is demonstrated in the examples:

$$\begin{matrix} 38.429 \\ 38.000 \end{matrix} \text{ mm} \qquad \begin{matrix} 192.00 \\ 191.86 \end{matrix} \text{ mm}$$

It should be noted that with dimensions in U.S. customary units, each dimension contains the same number of decimal places as the applicable tolerance. Examples illustrating this are:

$$\begin{matrix} .752 \\ .748 \end{matrix} \text{ in.} \qquad 1.268 \pm .005 \text{ in.}$$

$$1.630 \begin{matrix} +.001 \\ -.010 \end{matrix} \text{ in.} \qquad 98.000 \pm .006 \text{ in.}$$

6-2 CONVERSION OF TOLERANCED DIMENSIONS TO SI UNITS

6-2.1 GENERAL CONSIDERATIONS

The requirement for converting toleranced dimensions generally involves the conversion of a dimension in inches with a tolerance in inches to an equivalent dimension and tolerance in millimetres (Refs. 2 and 3). As the conversion factor, 1 in. = 25.4 mm, is an exact one, the number of significant digits in a converted value is generally greater than is required or justified. It is thus necessary to round converted dimensions to an appropriate number of significant digits so that accuracy of the converted dimension is compatible with the accuracy of the original dimension. Additionally, the tolerances of the original dimension are converted to equivalent tolerances in the converted dimension.

Toleranced dimensions can be expressed in several ways. General tolerancing practices are given in American National Standard, ANSI Y14.5-1973, (Ref. 1); those practices specific to SI drawings and dual dimensioned drawings are summarized in pars. 6-1 and 6-3 of this handbook.

Generally tolerancing is expressed as limits to a dimension or as an allowable plus and minus variation to a dimension. The following is an example in U.S. customary units of a dimension with tolerance expressed as limits:

$$\begin{matrix} .311 \\ .309 \end{matrix}$$

The limit .311 is the upper limit and .309 is the lower limit of the dimension. In general, limits are assumed to be absolute; i.e., .311 is assumed to have an infinite number of significant digits (zeros) to the right of the one-digit. This means that the corresponding dimension of a part must not exceed .311 in. and must not be less than .309 in. The differences between the limits, .002 in., is referred to as the tolerance. This same dimension with an equivalent tolerance may be expressed in the form:

$$.310 \pm .001 \text{ in.}$$

Note that the tolerance is still .002 in.; it is the range of acceptable dimensions. Frequently, the term tolerance is used to refer to .001 in. in this case. For consistency, the former use of tolerance is adhered to in this handbook.

As indicated in the preceding, limits are generally treated as absolute. In converting dimensions in inches to dimensions in millimetres, the limits cannot in general be converted exactly because of practical con-

siderations. Consider a specific case: convert .914 ± .004 in. to an equivalent dimension in millimetres. The upper limit is .918 in.; the corresponding dimension of the part cannot exceed .918 in. The limit .918 in. is converted to millimetres as follows:

$$.918 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 23.3172 \text{ mm}$$

Using the rules given in par. 4-2 for rounding numbers, a unit in the position of the last significant digit in the original limit is converted to millimetres. In this case .001 in. is converted as follows:

$$.001 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 0.0254 \text{ mm}$$

The limit in millimetres, 23.3172 mm, is then rounded such that a unit in the position of the last significant digit retained is equal to or less than 0.0254 mm. Thus the converted limit is rounded to 23.32 mm (note $0.01 \leq 0.0254$).

The conversion of the limit .918 in. to 23.32 mm has been made according to accepted and valid practices. These practices give acceptable results when applied to the conversion of the units of quantities which are not the dimensions of piece parts. The difficulty in the given example is simply that 23.32 mm is longer than .918 in. and .918 in. is an absolute upper limit. There are cases where the upper and lower limits specified by a toleranced dimension can be violated by a small amount without creating problems. But, if interchangeable parts are involved, it is likely that the limits cannot be exceeded. The paragraphs that follow describe acceptable methods for converting toleranced dimensions (Refs. 2 and 3). These methods apply specifically to the conversion of the units (inches to millimetres) of linear dimensions in engineering drawings. Examples are included to demonstrate applications of the methods.

6-2.2 TOLERANCED DIMENSIONS WITHOUT ABSOLUTE LIMITS

The method for converting the units of toleranced dimensions presented in this paragraph is specifically for the case where the original tolerance and limits are not absolute and can be violated to some extent. The method insures that even under worst case conditions the original limits are not altered by more than two percent of the tolerance. When limits are modified and, in particular, when the tolerance is increased, the impact of the change must be determined within the context of the original design criteria.

Table 6-1 is used in determining to what extent the limits of a converted dimension are rounded (Ref. 2). The method is demonstrated by the following examples:

Example No. 1: Convert the dimension 1.890 ± .012 in. to millimetres.

1. Express the dimension in terms of its limit.

$$1.890 + .012 \text{ in.} = 1.902 \text{ in.}$$
$$1.890 - .012 \text{ in.} = 1.878 \text{ in.}$$

2. Convert the limits to millimetres exactly.

$$1.902 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 48.3108 \text{ mm}$$

$$1.878 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 47.7012 \text{ mm}$$

3. Round limits according to guidelines in Table 6-1 as follows. From the original limits, the tolerance is 1.902 in. − 1.878 in. = .024 in. This tolerance is greater than .01 in. and is less than .1 in.; thus, from Table 6-1, the limits in millimetres should be rounded to the nearest 0.01 mm. The rounded limits are:

48.31 mm
47.70 mm

4. These limits can be expressed as a dimension with plus and minus tolerance as follows. The dimension is the mean value of the limits:

$$\frac{48.31 \text{ mm} + 47.70 \text{ mm}}{2} = 48.005 \text{ mm}$$

The tolerance is 48.31 mm − 47.70 mm = 0.61 mm, or 0.30 mm on each side of the mean. Thus the result can be written:

$$48.00 \pm 0.30 \text{ mm}$$

(Note that all quantities in millimetres in this example are rounded to the nearest 0.01 mm.)

5. The original tolerance, .024 in., can be converted to millimetres as follows:

$$.024 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 0.6096 \text{ mm}$$

Since the tolerance of the converted dimension is 0.60 mm, the tolerance has been tightened in this case.

6. It is instructive to compare the upper and lower limits in millimetres and the tolerances obtained in Steps 2, 3, and 4.

	Step No. 2	Step No. 3	Step No. 4
Upper limit	48.3108	48.31	48.30
Lower limit	47.7012	47.70	47.70
Tolerance	0.6096	0.61	0.60

The Step 2 limits are exact equivalents of the original limits in inches, and, therefore, are a valid basis for assessing the impact of the conversion process. Consider Step 3 results first. The tolerance is increased slightly, 0.0004 mm; this is probably negligible. The lower limit is smaller by 0.0012 mm and, while likely not significant, the original design should be studied to determine if this is the case. Consider the results of Step 4 next. The only change with respect to Step 3 results is that the upper limit has been made smaller by 0.01 mm and the tolerance has been decreased by the same amount. The decision as to which results to use always will depend upon the original design criteria.

TABLE 6-1

ROUNDING TOLERANCES OF LINEAR DIMENSIONS (Ref. 1)

Inches to Millimetres

Original Tolerance, in.		Fineness of Rounding, mm
at least	**less than**	
.000 01	0.000 1	0.000 01
.000 1	0.001	0.000 1
.001	0.01	0.001
.01	0.1	0.01
.1	1.	0.1

Example No. 2: Convert the dimension 1.950 ± .016 in. to millimetres.

1. Express the dimension in terms of its limits:

1.950 in. + .016 in. = 1.966 in.
1.950 in. − .016 in. = 1.934 in.

2. Convert the limits to millimetres exactly:

$$1.966 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 49.9364 \text{ mm}$$

$$1.934 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 49.1236 \text{ mm}$$

3. The original tolerance in inches is:

$$1.966 \text{ in.} - 1.934 \text{ in.} = .032 \text{ in.}$$

From Table 6-1, the converted limits should be rounded to the nearest 0.01 mm. Therefore the limits are:

49.94 mm
49.12 mm

In this case, the converted upper limit exceeds the original upper limit and the converted lower limit is smaller than the original lower limit. Thus the converted limits are "outside" the original limits at both ends.

4. The original tolerance in millimetres is:

$$49.9364 \text{ mm} - 49.1236 \text{ mm} = 0.8128 \text{ mm}$$

The tolerance of the converted limits is:

$$49.94 \text{ mm} - 49.12 \text{ mm} = 0.82 \text{ mm}$$

The increase in the tolerance as a percentage of the original tolerance is:

$$100\% \times \frac{0.82 \text{ mm} - 0.8128 \text{ mm}}{0.8128 \text{ mm}} \approx 0.89\%$$

This small increase is probably negligible.

6-2.3 DIMENSIONS WITH ABSOLUTE LIMITS

The method for converting the units of toleranced dimensions presented here applies to dimensions which have absolute limits that cannot be violated. The method is basically the same as the method for dimensions without absolute limits (see par. 6-2.2) except that rounding is always "toward the interior of the tolerance"; i.e., the upper limit is rounded downward to the next lower value and the lower limit is rounded upward to the next higher value. The method is demonstrated in the following examples:

Example No. 3: Convert the dimension 1.950 ± .016 in. to millimetres.

1. Express the dimension in terms of its limits:

$$1.950 \text{ in.} + .016 \text{ in.} = 1.966 \text{ in.}$$
$$1.950 \text{ in.} - .016 \text{ in.} = 1.934 \text{ in.}$$

2. Convert the limits to millimetres exactly:

$$1.966 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 49.9364 \text{ mm}$$

$$1.934 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 49.1236 \text{ mm}$$

3. The original tolerance in inches is .032 in. From Table 6-1, the converted limits should be rounded toward the interior and to the nearest 0.01 mm; i.e., 49.9364 is rounded to 49.93 and 49.1236 is rounded to 49.13. The converted limits are:

49.93 mm
49.13 mm

Note that this example is the same as Example No. 2, par. 6-2.2, except that here the limits are treated as absolute. In par. 6-2.2, the converted lower and upper limits are 49.12 mm and 49.94 mm, respectively, both of which are outside the original tolerances. Here both converted limits are inside the original tolerances.

Example No. 4: Convert the dimension 2.691 ± .004 in. to millimetres.

1. Express the dimension in terms of its limits:

$$2.691 \text{ in.} + .004 \text{ in.} = 2.695 \text{ in.}$$
$$2.691 \text{ in.} - .004 \text{ in.} = 2.687 \text{ in.}$$

2. Convert limits to millimetres exactly:

$$2.695 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 68.4530 \text{ mm}$$
$$2.687 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 68.2498 \text{ mm}$$

3. The original tolerance is 2 × .004 in. = .008 in. From Table 6-1, the converted limits are rounded toward the interior and to the nearest 0.001 mm. Thus the limits are:

68.453 mm
68.250 mm

Note that in this case, the result is not dependent upon the original limits being absolute. Rounding the converted limits in the normal manner results in no change in the upper limit and the lower limit is rounded toward the interior of the tolerance; i.e., it is increased.

6-2.4 SPECIAL SITUATIONS

A number of situations can arise in converting the units of toleranced dimensions which cannot be covered by specific rules and general approaches. In each case, the better one understands the functional requirements of the part specified, the manner in which the drawing dimensions and tolerances are used in manufacturing the part, and how the part will be inspected and what tools and gages are used in the inspection process, the more certain he can be that the critical dimensions and tolerances have been properly converted to a different system of units in a manner that is convenient and useful in both manufacturing and inspection processes.

It is not practical to try to cover in this handbook all or even a significant number of situations that may be encountered. The following example will illustrate one approach to a not completely straightforward dimensioning problem:

Example No 5: The side view of a truncated cone appears in Fig. 6-1. The taper of the cone is .100 in. per in. The diameter of the cone is specified at a single reference plane 1.000 in. from the base (the large end). The diameter at the reference plane is .610 ± .005 in. Convert the given dimensions in customary units to dimensions in SI units.

1. A taper of .100 in. per in. is a ratio, a dimensionless quantity. The equivalent SI dimension is 0.100 mm per mm or it can be given as a ratio 0.001:1 (see par. 6-1).

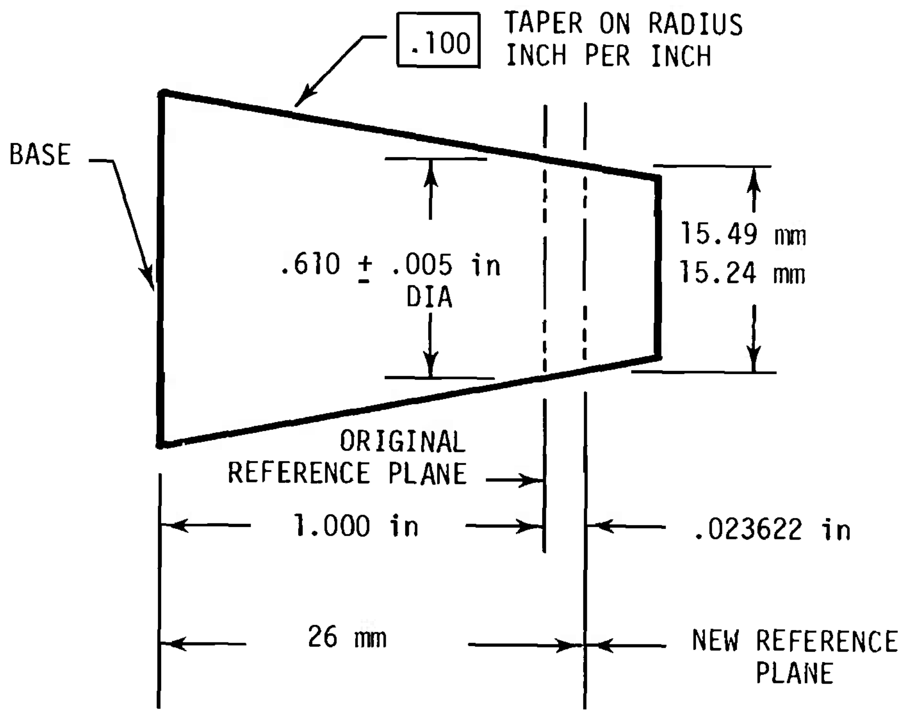
2. The approach to specifying the diameter of the cone will be first to define a new reference plane in SI units "close to the original" on the basis of convenience. The original reference plane is 1.000 in. from the base; converting this to millimetres gives:

$$1.000 \text{ in.} \times \frac{25.4 \text{ mm}}{\text{in.}} = 25.4 \text{ mm}$$

The new reference plane will be defined to be 26 mm from the base.

3. The next step will be to calculate a new diameter at the new reference plane. The new reference plane is 0.6 mm farther from the base than the original reference plane. This difference is converted to inches as follows:

$$0.6 \text{ mm} \times \frac{1 \text{ in.}}{25.4 \text{ mm}} = .023622 \text{ in.}$$



NOTE: THIS DRAWING IS FOR THE PURPOSE OF ILLUSTRATING THE CONVERSION OF UNITS OF DIMENSIONS. THE USE OF SYMBOLS, DIMENSIONS, UNITS, ETC. ARE NOT ACCEPTABLE FOR ENGINEERING DRAWING.

Figure 6-1. Reference Planes in Truncated Cone

Since the taper is .100 in. per in., the change in the radius of the cone (a decrease, see Fig. 6-1) going from the original reference plane to the new reference plane is:

$$.100\,\frac{\text{in.}}{\text{in.}} \times .023622\text{ in.} = .0023622\text{ in.}$$

Therefore the diameter at the new reference plane is:

$$.610\text{ in.} - 2 \times .0023622\text{ in.} = .6052756\text{ in.}$$

Rounding this to three significant digits and assuming that the tolerance for the diameter does not change give the following dimension for diameter at the new reference plane:

$$.605 \pm .005\text{ in.}$$

4. Finally, the diameter .605 ± .005 in. is converted to millimetres. The limits of the dimension are:

$$.605\text{ in.} + .005\text{ in.} = .610\text{ in.}$$
$$.605\text{ in.} - .005\text{ in.} = .600\text{ in.}$$

The limits are converted to millimetres in the calculations:

$$.610\text{ in.} \times \frac{25.4\text{ mm}}{\text{in.}} = 15.494\text{ mm}$$
$$.600\text{ in.} \times \frac{25.4\text{ mm}}{\text{in.}} = 15.240\text{ mm}$$

The original tolerance is .010 in. From Table 6-1, the converted limits should be rounded to the nearest 0.01 mm:

15.49 mm
15.24 mm

5. Thus, the cone can be specified as having a taper of 0.100 mm per mm, with a diameter between the limits 15.24 mm and 15.49 mm at a reference plane 26 mm from the base.

6. The height of the cone has not be considered in this example. The units of this dimension would be converted by the methods of par. 6-2.2 or 6-2.3.

6-2.5 INCH-MILLIMETRE CONVERSION TABLES

Tables 6-2 and 6-3 are included as aids in converting the units of linear dimensions in engineering drawings from inches to millimetres. Table 6-2 can be used to make exact conversions. Table 6-3 allows a direct conversion from inches expressed as common fractions to millimetres. Methods for using the tables are given in footnotes.

6-3 FORMATS FOR DIMENSIONING IN MILITARY ENGINEERING DRAWINGS

In general, the units used on an engineering drawing should be the units that are most compatible with the requirements of the user of the drawing. Thus, the great majority of military drawings (including those being prepared now) should use U.S. customary units (Ref. 1).

As metrication progresses in the U.S. and particularly in the DOD and DARCOM, the design or development of piece parts, components, systems, specifications, and standards will with increasing frequency use the International System of Units. As this takes place, the drawings associated with the parts, systems, etc., should use SI units. (These drawings should *not* use dual-dimensioning except under certain circumstances discussed in the paragraph that follows.) Thus, the conversion of engineering drawings to SI is a binary step. When a part is designed in customary units and will be manufactured using machines and machine tools designed for customary units, the associated drawings should use customary units; when the design of a part is based on metric units and metric machines are to be used in the manufacture of the parts, then SI engineering drawings should be prepared.

TABLE 6-2

INCH-MILLIMETRE EQUIVALENTS (Ref. 2)

NOTE -- All values in this table are exact, based on the relation 1 in. = 25.4 mm. By manipulation of the decimal point any decimal value or multiple of an inch may be converted to its exact equivalent in millimetres.*

in.	0	1	2	3	4	5	6	7	8	9
					mm					
0		25.4	50.8	76.2	101.6	127.0	152.4	177.8	203.2	228.6
10	254.0	279.4	304.8	330.2	355.6	381.0	406.4	431.8	457.2	482.6
20	508.0	533.4	558.8	584.2	609.6	635.0	660.4	685.8	711.2	736.6
30	762.0	787.4	812.8	838.2	863.6	889.0	914.4	939.8	965.2	990.6
40	1016.0	1041.4	1066.8	1092.2	1117.6	1143.0	1168.4	1193.8	1219.2	1244.6
50	1270.0	1295.4	1320.8	1346.2	1371.6	1397.0	1422.4	1447.8	1473.2	1498.6
60	1524.0	1549.4	1574.8	1600.2	1625.6	1651.0	1676.4	1701.8	1727.2	1752.6
70	1778.0	1803.4	1828.8	1854.2	1879.6	1905.0	1930.4	1955.8	1981.2	2006.6
80	2032.0	2057.4	2082.8	2108.2	2133.6	2159.0	2184.4	2209.8	2235.2	2260.6
90	2286.0	2311.4	2336.8	2362.2	2387.6	2413.0	2438.4	2463.8	2489.2	2514.6
100	2540.0	...	...	...	...	...	...	...	...	...

*Example: Convert 132.19 in. to millimetres.

Note: 132.198 in. = 100 in. + 32 in. + .19 in.

Convert separately: 100 in. = 2540 mm; 32 in. = 812.8 mm; .19 in. = 482.6×10^{-2}

Therefore: 132.19 in. = (2540 + 812.8 + 4.826)mm = 3357.636 mm (exact)

TABLE 6-3

INCH-MILLIMETRE EQUIVALENTS OF DECIMAL AND COMMON FRACTIONS (Ref. 2)

Inch	1/2's	1/4's	8ths	16ths	32nds	64ths	Millimetres	Decimals of an Inch
						1	0.397	0.015 625
					1	2	0.794	0.031 25
						3	1.191	0.046 875
				1	2	4	1.588	0.062 5
						5	1.984	0.078 125
					3	6	2.381	0.093 75
						7	2.778	0.109 375
			1	2	4	8	3.175	0.125 0
						9	3.572	0.140 625
					5	10	3.969	0.156 25
						11	4.366	0.171 875
				3	6	12	4.762	0.187 5
						13	5.159	0.203 125
					7	14	5.556	0.218 75
						15	5.953	0.234 375
		1	2	4	8	16	6.350	0.250 0
						17	6.747	0.265 625
					9	18	7.144	0.281 25
						19	7.541	0.296 875
				5	10	20	7.938	0.312 5
						21	8.334	0.328 125
					11	22	8.731	0.343 75
						23	9.128	0.359 375
			3	6	12	24	9.525	0.375 0
						25	9.922	0.390 625
					13	26	10.319	0.406 25
						27	10.716	0.421 875
				7	14	28	11.112	0.437 5
						29	11.509	0.453 125
					15	30	11.906	0.468 75
						31	12.303	0.484 375
	1	2	4	8	16	32	12.700	0.500 0
						33	13.097	0.515 625
					17	34	13.494	0.531 25
						35	13.891	0.546 875
				9	18	36	14.288	0.562 5
						37	14.684	0.578 125
					19	38	15.081	0.593 75
						39	15.478	0.609 375
			5*	10	20	40	15.875	0.625 0
						41	16.272	0.640 625
					21	42	16.669	0.656 25
						43	17.066	0.671 875
				11	22	44	17.462	0.687 5
						45	17.859	0.703 125
					23	46	18.256	0.718 75
						47	18.653	0.734 375
		3	6	12	24	48	19.050	0.750 0
						49	19.447	0.765 625
					25	50	19.844	0.781 25
						51	20.241	0.796 875
				13	26	52	20.638	0.812 5

*The quantity 5/8 in. is equivalent to 15.875 mm and to .625 0 in.

The procedure known as dual dimensioning is one in which both U.S. customary and SI units are used on the same engineering drawing (Ref. 1). The procedure is not recommended for implementing the change to the SI system of units in the DOD; it is a form of dimensioning which is used where interchangeable parts are to be manufactured using both U.S. customary and SI units. Dual dimensioning may involve specifying each dimension in customary units and SI units, or, specifying each dimension in one system of units and including on the drawing a table giving equivalent dimensions in both systems.

6-3.1 ENGINEERING DRAWINGS USING U.S. CUSTOMARY UNITS

U.S. customary units are commonly used on military engineering drawings. These drawings should contain the note: UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN INCHES. Practices applicable to these drawings are specified in American National Standard ANSI, Y14.5-1973, (Ref. 1).

It is acceptable to use a limited number of SI dimensions by including the unit symbol with the dimension. The following are typical examples:

←—0.32 ± 0.0012 mm—→

16.28 mm
←————————————→
16.06 mm

Practices relevant to the SI dimensions are given in par. 6-2.

6-3.2 ENGINEERING DRAWINGS USING SI UNITS

Engineering drawings using SI units usually are dimensioned in millimetres. These drawings should contain the note: UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN MILLIMETRES. Practices applicable to these drawings are specified in American National Standard ANSI, Y14.5-1973 (Ref. 1). Those procedures and practices applicable to SI dimensions which are different from those applicable to dimensions in U.S. customary units are summarized in par. 6-3.3. Conversion of dimension values and tolerances to SI units is covered in par. 6-2.

6-3.3 DUAL DIMENSIONING

The procedure known as "dual dimensioning" is one of showing linear dimensions, in both inches and millimetres, as adjacent values at each dimension in a drawing (Ref. 1). Since dual dimensioning is applicable to drawings of interchangeable parts to be manufactured in both U.S. customary units and SI units, it is particularly important that the conversion of dimension values and tolerances from inches to millimetres or millimetres to inches be performed according to the guidelines given in par. 6-2.

The dual dimensioned drawing must clearly identify which units are U.S. customary and which units are SI. Two methods are available for distinguishing units: the position method and the bracket method.

In the *position method* of dual dimensioning the millimetre-dimension is above the inch-dimension and separated from it by a horizontal line or the millimetre-dimension is to the left of the inch-dimension and separated from it by a slash. These methods are illustrated by the following examples:

31.318 ± 0.076
←————————————→
1.233 ± .003

31.394
31.242
←————————————→
1.236
1.230

←—31.318 ± 0.076/1.233 ± .003—→

One method of identifying inch- and millimetre-positions should be used consistently on a single drawing. The drawing must contain an illustration or note giving the positions of the inch- and millimetre-dimensions. Typical illustrations for this purpose are:

$$\frac{\text{MILLIMETRE}}{\text{INCH}}$$

MILLIMETRE/INCH

If it is desired, the positions of the inch- and millimetre-dimensions can be reversed but it must be done consistently for a single drawing. Examples of this form of positional dual dimensioning are:

$$\xleftrightarrow[31.318 \pm 0.076]{1.233 \pm .003}$$

$$\longleftarrow 1.233 \pm .003/31.318 \pm 0.076 \longrightarrow$$

Appropriate illustrations to be included on the drawing for the reversed positions are:

$$\frac{\text{INCH}}{\text{MILLIMETRES}}$$

INCH/MILLIMETRES

The *bracket method* is to enclose either the millimetre-dimension or the inch-dimension in square brackets, i.e., [ ]. This must be done consistently for a single drawing. The position of the bracketed dimension can be above, below, to the right of, or to the left of the other dimension; the position to be consistent to the extent practical in a single drawing. Examples are:

Above:

$$\begin{array}{c}[31.318 \pm 0.076] \\ \longleftarrow 1.233 \pm .003 \longrightarrow\end{array}$$

Below:

$$\begin{array}{c}\longleftarrow 1.233 \pm .003 \longrightarrow \\ [31.318 \pm 0.076]\end{array}$$

Below:

$$\begin{array}{c}\xleftrightarrow[1.230]{1.236} \\ \\ \begin{bmatrix}31.394 \\ 31.242\end{bmatrix}\end{array}$$

Right:

$$\longleftarrow 1.233 \pm .003\ [31.318 \pm 0.076] \longrightarrow$$

Left:

$$\longleftarrow \begin{bmatrix}1.236 \\ 1.230\end{bmatrix} \begin{bmatrix}31.394 \\ 31.242\end{bmatrix} \longrightarrow$$

Typical illustrations to identify the method being used in a drawing are:

[MILLIMETRE]
INCH

[INCH] MILLIMETRE

As stated previously, a note may be used on a drawing to convey the method of dual dimensioning being used in a drawing. Examples of such notes are:

DIMENSIONS IN [ ] ARE MILLIMETRES

DIMENSIONS IN [ ] ARE INCHES

Existing drawings which are dimensioned in fractions of an inch can be dual dimensioned simply by adding the millimetre-equivalents adjacent to the inch-dimensions. It generally is assumed that the accuracy implied is equivalent to that of a decimal with two significant digits to the right of the decimal. Typical examples are:

$$\longleftarrow \frac{61.91 \pm 0.40}{2\frac{7}{16} \pm \frac{1}{64}} \longrightarrow$$

$$\longleftarrow \begin{matrix}[61.91 \pm 0.40] \\ 2\frac{7}{16} \pm \frac{1}{64}\end{matrix} \longrightarrow$$

Generally, it is desirable to express all fractions in a drawing as decimal fractions except where the fraction designates nominal sizes. Nominal sizes are not converted or dual dimensioned. This includes nominal thread sizes, pipe sizes, wood cross-sectional sizes, etc.

Units for quantities other than length which appear on dual dimensioned drawings can and should be expressed as dual dimensions and in the same manner as the dimensions of length. This is true for units in notes and text as well as units that appear on the part drawing. In general, any of the methods for dual dimensioning lengths given in the preceding paragraphs can be used. Values of density in U.S. customary units and SI units, as examples, can be specified in a drawing in the following ways:

[2.19 lbm/ft^3] 35.080 kg/m^3

$$\frac{35.080\ kg/m^3}{2.19\ lbm/ft^3}$$

Note that with quantities other than length, the unit symbols *are* used.

Angles given in degrees, minutes, and seconds or in degrees and decimal fractions of a degree can be used with either U.S. customary units and SI units and, therefore, can be used on dual dimensioned drawings without conversion or dual dimensioning of the angles.

Some quantities are dimensionless quantities and do not require dual dimensioning. For example taper is a ratio which can be specified independent of units. A specific taper may be specified as .006 in. per in. on a drawing using U.S. customary units or as 0.006 mm per mm on an SI drawing. The same taper can be specified as a ratio .006:1 on either type of drawing or on a dual dimensioned drawing.

In all SI drawings and dual dimensioned drawings the diameter symbol ϕ is used in place of the abbreviation DIA.

The U.S. practice of using third angle projection on drawings is correct for drawings using SI units and dual dimensioning. Since many countries using SI units use first angle projection on drawings, U.S. drawings using SI units or dual dimensioning should specify the angle of projection in order to avoid confusion. Appropriate symbols and notes are given in American National Standard, Y14.4-1957 (Ref. 4).

Dual dimensioned drawings illustrating a number of the described practices are presented in Figs. 6-2 and 6-3 (Ref. 1).

6-3.4 DUAL DIMENSIONING, TABULAR FORMAT

American National Standard, ANSI Y14-5-1973, allows the tabular listing of U.S. customary and SI unit equivalents as an alternative to dual dimensioning practices as specified in par. 6-3.3 (Ref. 1). In such cases, the drawing dimensions are given in either U.S. customary units or SI units depending upon the units used in the design. The values of all dimensions are duplicated in a table on the drawing and equivalent dimensions in the other system of units are included in the table. Table captions must identify which columns are inch-dimensions and millimetre-dimensions. An example is presented in Fig. 6-4.

Computer programs are available for generating equivalent dimensions with the computer outputing the data directly in tabular format for attaching to a drawing or transfer to a drawing. The inputs can be either inch-dimensions or millimetre-dimensions. A package consisting of computer programs on magnetic tape developed by Caterpillar Tractor Co. and General Motors Corporation — documentation explaining how to used the programs and how to run the programs on different computers, and test problems to verify correct operation — can be obtained by writing to Conversion Package, Room B-311, Chemistry Building, National Bureau of Standards, Washington, DC 20234 for ordering information (Ref. 5).

The drawing with dual dimensions specified in tabular format is generally easier to use than one with adjacent dual dimensions placed at each dimension line. The adjacent positioning method of dual dimensioning — particularly in the case of a complex, high precision part — can result in a drawing being so cluttered with dimensions that it is difficult to take dimensions from the drawing, and the likelihood of making an error is increased.

REFERENCES

1. American National Standards Institute, *Dimensioning and Tolerancing for Engineering Drawings*, ANSI Y14.5-1973, ANSI, NY, 1973.
2. American National Standards Institute, American Society for Testing and Materials, *Standardfr Metric Practice*, ASTM E 380, ANSI, NY, January 1976.
3. International Organization for Standardization, *Conversion of Toleranced Dimensions from Inches to Millimeters and Vice Versa*, ISO Recommendation R370, ISO, Switzerland, May 1964.
4. American National Standards Institute, *Projections*, ANSI Y14.3-1957, ANSI, NY, 1957.
5. NBS LC 1057, *Computer Program Package for Metric Conversion*, Department of Commerce, National Bureau of Standards, January 1975.

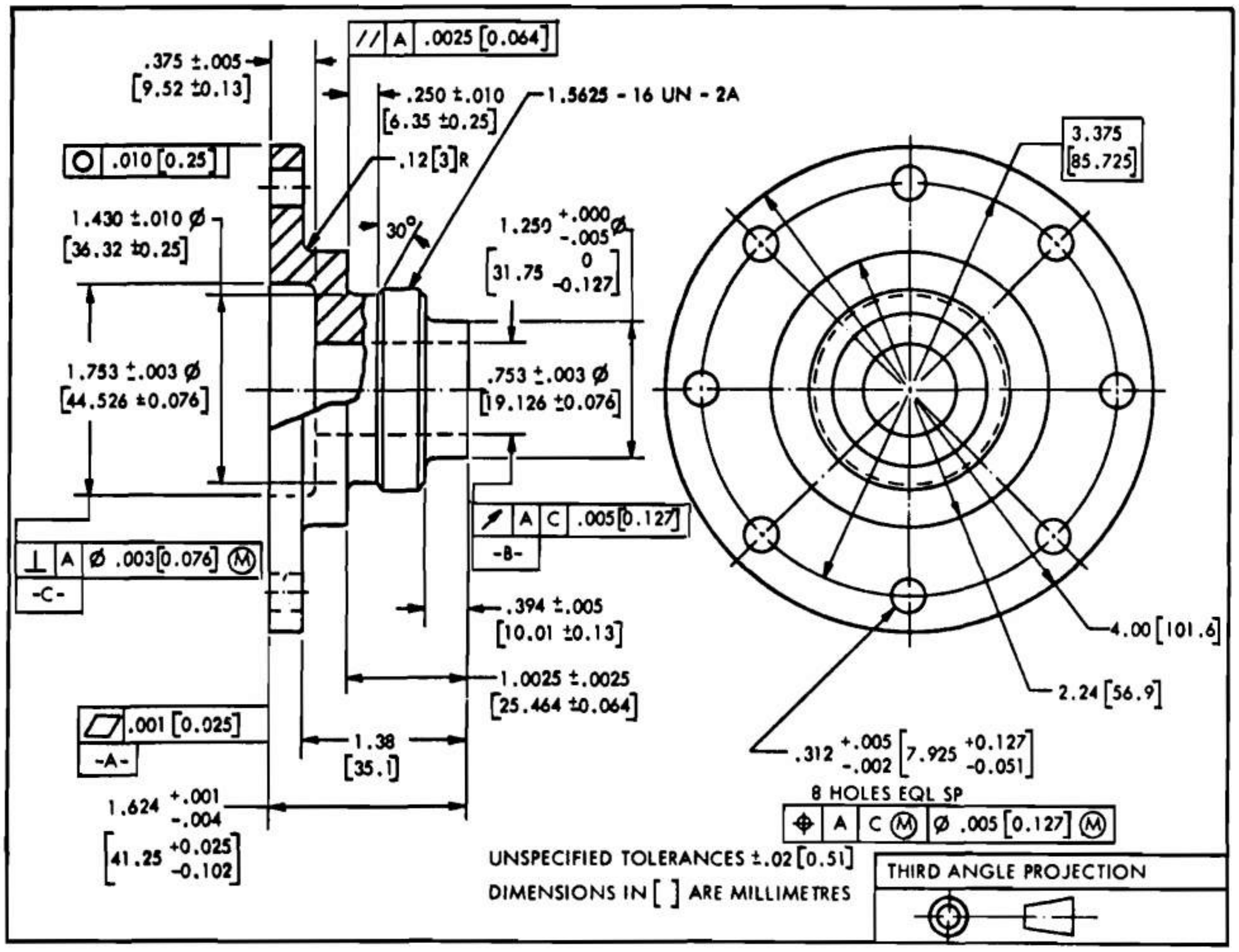


Figure 6-2. Dual Dimensioned Drawing Using [ ] Notation (Ref. 1)

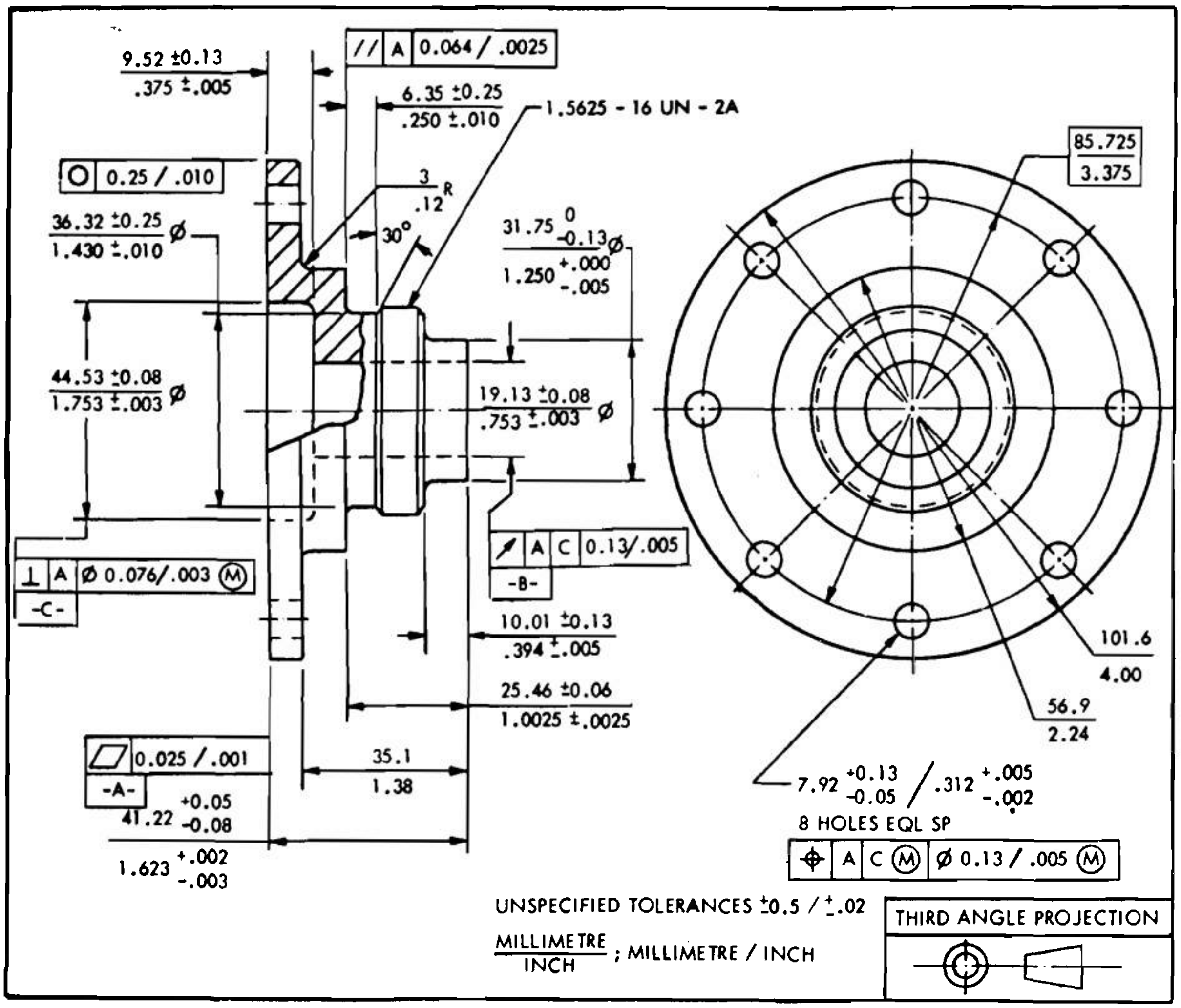
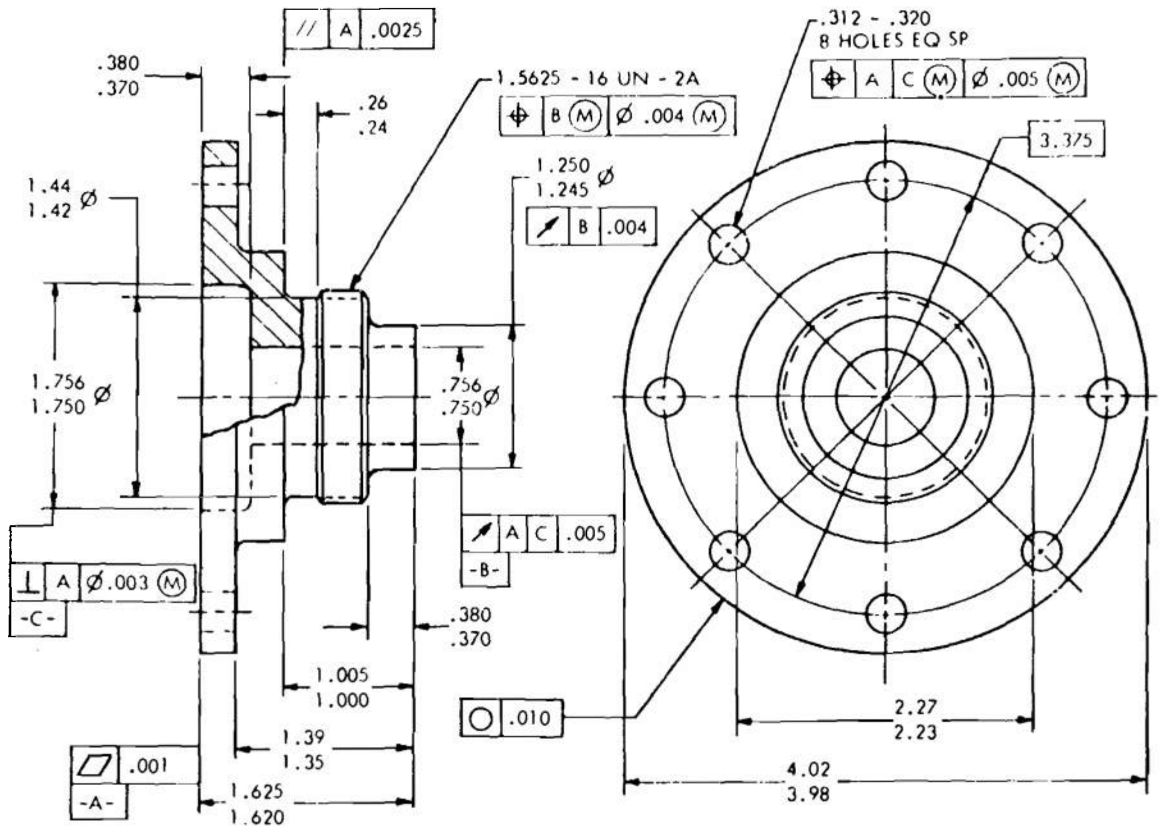


Figure 6-3. Dual Dimensioned Drawing Using Position Notation (Ref. 1)

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
.26	6.60
.24	6.10
.320	8.128
.312	7.925
.380	9.65
.370	9.40
.756	19.202
.750	19.050
1.005	25.527
1.000	25.400
1.250	31.750
1.245	31.623
1.39	35.31
1.35	34.29
1.44	36.58
1.42	36.07
1.5625	39.688
1.625	41.275
1.620	41.148
1.752	44.501
1.750	44.450
2.27	57.66
2.23	56.64
3.375	85.72
4.02	102.11
3.98	101.09



ALL DIMENSIONS ARE IN INCHES

Figure 6-4. Tabular Listing of Inch-Millimetre Equivalents in Engineering Drawing (Drawing from Ref. 1)

CHAPTER 7
EXAMPLES

Four examples of situations involving the conversion of units to the International System of Units are presented in this chapter. These examples are taken from the Engineering Design Handbook series published by the US Army and MIL-HDBK-759, Human Factors Engineering Design for Army Materiel.

The examples were all chosen to illustrate the kinds of problems that can be encountered; they were not selected on the basis of difficulty. The examples illustrate the conversion of the units of equations, tables of data, graphs, and special quantities.

7-1 BODY DIMENSIONS FOR USE IN EQUIPMENT DESIGN

Reference: MIL-HDBK-759, *Human Factors Engineering Design for Army Materiel.*

Human factors engineering must be included in equipment design in order to minimize maintenance problems and optimize work performance. Human factors engineering relates man's size, strength, and other capabilities to the operation of equipment and the performance of work.

Ironically, anthropometric data are collected in metric measurements; the problem has been the accurate conversion to U.S. customary units. The required adoption of the metric system will solve this problem. However, during the transition period it may be necessary to convert from the SI system of units to the U.S. customary units. Figs. 7-1 and 7-2, taken from MIL-HDBK-759, show anthropometric data in both the SI and U.S. customary units. The conversion method using data from Figs. 7-1 and 7-2, though simple, is illustrated in the paragraphs that follow.

Rules for the use of prefixes in par. 3-3 state that the preferred prefixes are those representing multiples or submultiples of 10^3; i.e., for length one should use km, m, mm, μm, etc. However, in the case of body measurements the centimetre is a very convenient unit; for example, consider the combinations 98-64-91 cm as compared with 980-640-910 mm. In the clothing industry and the medical field, measurements of the human body are taken more frequently in centimetres than millimetres. Thus centimetres are used in Figs. 7-1 and 7-2.

The linear dimensions — in this example from centimetres to inches — are converted as described in par. 4-1 using the unit equality 1 in. = 0.0254 m from Table 5-1 or 5-2. Use also is made of the relationship 1 cm = 0.01 m from Table 2-4. Thus for the chest depth measurement of 18.9 cm for the 1st percentile in Fig. 7-1:

$$18.9\,\text{cm} \times \frac{0.01\,\text{m}}{\text{cm}} \times \frac{\text{in.}}{0.0254\,\text{m}} = 7.44\,\text{in.} \qquad (7\text{-}1a)$$

Rounded to the nearest 0.1 in., the value becomes 7.4 in. as indicated in Fig. 7-1.

The conversion of the weight (really mass) of the 1st percentile, using the equality 1 lbm = $4.535\,173\,84 \times 10^{-1}$ kg from Table 5-2 follows:

$$52.6\,\text{kg} \times \frac{\text{lbm}}{4.535\,173\,84 \times 10^{-1}\,\text{kg}} = 115.963\,149\,9\,\text{lbm} \qquad (7\text{-}1b)$$

Rounded to the nearest 0.1 lbm, the value becomes 116 lbm as indicated in Fig. 7-2.

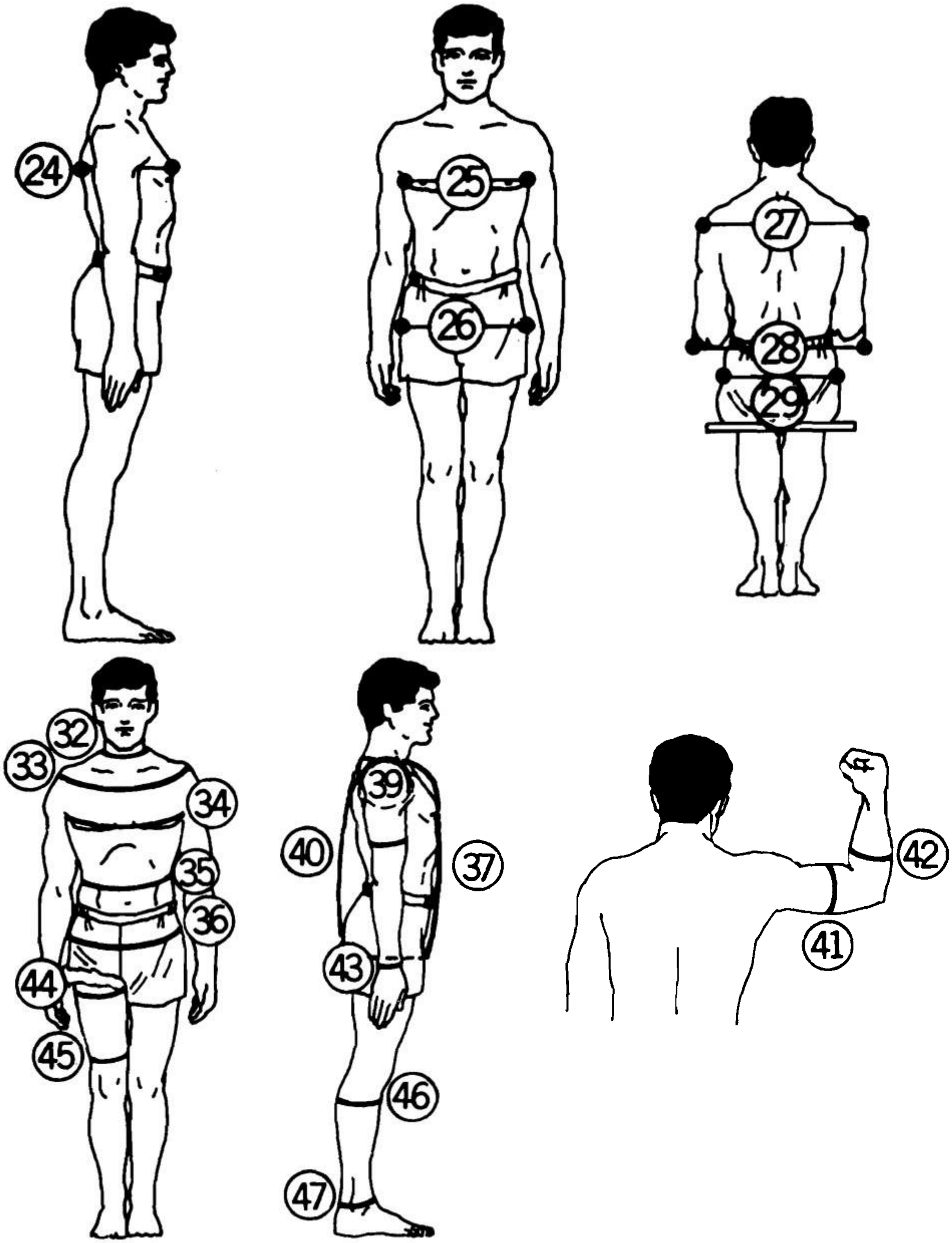


Figure 7-1. US Army Men (1966): Breadth and Circumference Measurements

No.	Measurements	1st	2nd	5th	10th	25th	50th	75th	90th	95th	98th	99th	Range (1st-99th)
		Percentiles in Centimeters											
	BREADTH MEASUREMENTS												
24	Chest Depth	19.2	19.6	20.2	20.8	21.8	23.0	24.4	25.8	26.7	27.9	28.8	9.6
25	Chest Breadth	26.1	26.6	27.3	28.0	29.1	30.4	31.9	33.4	34.4	35.5	36.4	10.3
26	Hip Breadth, Standing	29.1	29.5	30.2	30.8	31.8	33.0	34.4	35.8	36.7	37.8	38.6	9.5
27	Shoulder Breadth	40.0	40.6	41.5	42.3	43.6	45.2	47.0	48.6	49.8	51.1	52.1	12.1
28	Forearm-Forearm Breadth	37.9	38.6	39.8	40.9	43.0	45.6	48.6	51.6	53.6	55.9	57.6	19.7
29	Hip Breadth, Sitting	29.5	30.0	30.7	31.4	32.5	33.9	35.6	37.3	38.4	39.8	40.7	11.2
		Percentiles in Inches											
24	Chest Depth	7.6	7.7	8.0	8.2	8.6	9.1	9.6	10.1	10.5	11.0	11.4	3.8
25	Chest Breadth	10.3	10.5	10.8	11.0	11.4	12.0	12.6	13.1	13.5	14.0	14.3	4.0
26	Hip Breadth, Standing	11.4	11.6	11.9	12.1	12.5	13.0	13.6	14.1	14.5	14.9	15.2	3.8
27	Shoulder Breadth	15.7	16.0	16.3	16.6	17.2	17.8	18.5	19.2	19.6	20.1	20.5	4.8
28	Forearm-Forearm Breadth	14.9	15.2	15.7	16.1	16.9	18.0	19.1	20.3	21.1	22.0	22.7	7.8
29	Hip Breadth, Sitting	11.6	11.8	12.1	12.3	12.8	13.4	14.0	14.7	15.1	15.6	16.0	4.4
	CIRCUMFERENCES	Percentiles in Centimeters											
32	Neck Circumference	33.0	33.5	34.2	34.8	35.9	37.3	38.7	40.1	41.0	42.0	42.6	9.6
33	Shoulder Circumference	99.8	101.2	103.3	105.3	108.8	112.8	117.1	121.4	124.2	127.7	130.2	30.4
34	Chest Circumference	80.9	82.2	84.1	85.9	89.1	93.0	97.7	102.6	105.9	109.9	112.8	31.9
35	Waist Circumference	66.3	67.7	69.7	71.3	74.5	78.9	84.7	91.4	95.9	101.6	105.6	39.3
36	Hip Circumference	82.0	83.3	85.1	86.8	89.8	93.6	97.9	102.5	105.5	109.3	112.0	30.0
37	Vertical Trunk Circum.	145.4	147.5	150.6	153.5	158.3	163.8	169.5	175.1	178.8	182.9	185.9	40.5
39	Arm Scye Circumference	37.7	38.4	39.6	40.6	42.3	44.3	46.5	48.7	50.3	52.3	53.8	16.1
40	Biceps Circum., Relaxed	23.9	24.4	25.3	26.1	27.5	29.2	31.2	33.1	34.2	35.6	36.6	12.7
41	Biceps Circum., Flexed	26.5	27.1	28.0	28.9	30.4	32.1	34.0	35.9	37.0	38.4	39.4	12.9
42	Forearm Circum., Flexed	24.8	25.3	26.1	26.8	28.0	29.3	30.8	32.2	33.1	34.3	35.1	10.3
43	Wrist Circumference	15.1	15.3	15.7	16.0	16.5	17.0	17.6	18.2	18.6	19.0	19.3	4.2
44	Upper Thigh Circumference	45.5	46.5	48.1	49.5	52.0	55.1	58.5	61.8	63.9	66.1	67.6	22.1
45	Lower Thigh Circumference	32.7	33.4	34.4	35.5	37.5	40.1	43.0	45.6	47.2	48.9	49.9	17.2
46	Calf Circumference	30.8	31.4	32.4	33.2	34.7	36.5	38.3	40.1	41.2	42.5	43.4	12.6
47	Ankle Circumference	19.7	20.0	20.5	20.9	21.7	22.6	23.8	24.6	25.2	25.9	26.4	6.7
		Percentiles in Inches											
32	Neck Circumference	13.0	13.2	13.5	13.7	14.2	14.7	15.2	15.8	16.1	16.5	16.8	3.8
33	Shoulder Circumference	39.3	39.8	40.7	41.5	42.8	44.4	46.1	47.8	48.9	50.3	51.3	12.0
34	Chest Circumference	31.8	32.4	33.1	33.8	35.1	36.6	38.5	40.4	41.7	43.4	44.4	12.6
35	Waist Circumference	26.1	26.7	27.4	28.1	29.3	31.0	33.4	36.0	37.8	40.0	41.6	15.5
36	Hip Circumference	32.3	32.8	33.5	34.2	35.4	36.8	38.8	40.4	41.6	43.0	44.1	11.8
37	Vertical Trunk Circum.	57.2	58.1	59.3	60.4	62.3	64.5	66.7	68.9	70.3	72.0	73.2	16.0
39	Arm Scye Circumference	14.8	15.1	15.6	16.0	16.7	17.4	18.3	19.2	19.8	20.6	21.2	6.4
40	Biceps Circum., Relaxed	9.4	9.6	10.0	10.3	10.8	11.5	12.3	13.0	13.5	14.0	14.4	5.0
41	Biceps Circum., Flexed	10.4	10.7	11.0	11.4	12.0	12.6	13.4	14.1	14.6	15.1	15.5	5.1
42	Forearm Circum., Flexed	9.8	10.0	10.3	10.5	11.0	11.6	12.1	12.7	13.0	13.5	13.8	4.0
43	Wrist Circumference	5.9	6.0	6.2	6.3	6.5	6.7	6.9	7.2	7.3	7.5	7.6	1.7
44	Upper Thigh Circumference	17.9	18.3	18.9	19.5	20.5	21.7	23.0	24.3	25.1	26.0	26.6	8.7
45	Lower Thigh Circumference	12.9	13.1	13.6	14.0	14.8	15.8	16.9	18.0	18.6	19.2	19.6	6.7
46	Calf Circumference	12.2	12.4	12.8	13.1	13.7	14.4	15.1	15.8	16.2	16.7	17.1	4.9
47	Ankle Circumference	7.8	7.9	8.1	8.2	8.5	8.9	9.3	9.7	9.9	10.2	10.4	2.6

Figure 7-1. (cont'd)

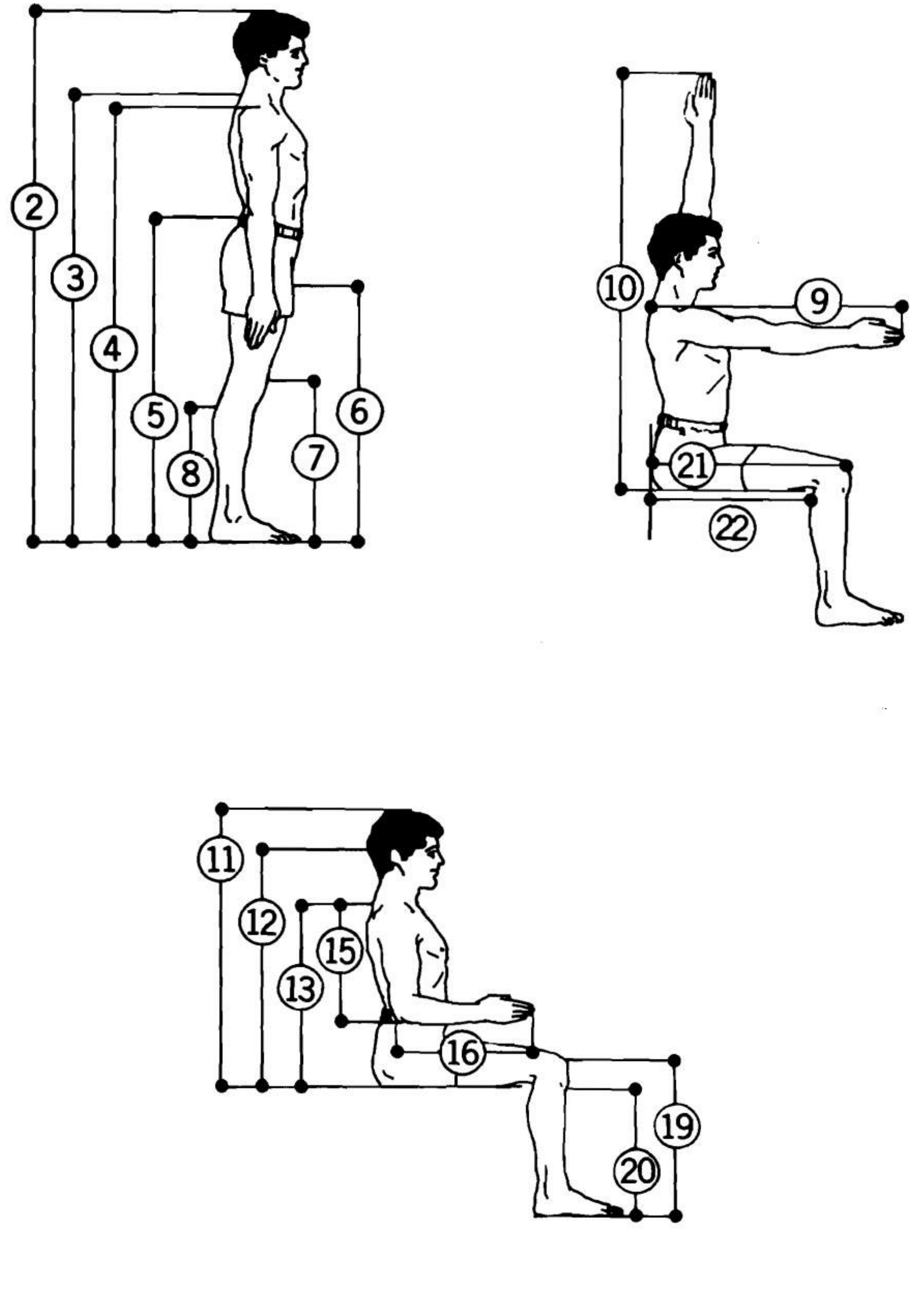


Figure 7-2. US Army Men (1966): Standing and Sitting Measurements

No.	Measurements	1st	2nd	5th	10th	25th	50th	75th	90th	95th	98th	99th	Range (1st-99th)
		Percentiles in Centimeters											
1	Weight (kilograms)	52.6	54.5	57.4	60.0	64.8	71.0	78.4	86.3	91.6	98.3	103.0	50.4
	STANDING MEASUREMENTS												
2	Stature	158.9	160.9	163.8	166.2	170.1	174.4	178.9	183.0	185.6	188.4	190.3	31.4
3	Cervicale Height	134.4	136.5	139.3	141.6	145.3	149.5	153.8	157.8	160.2	162.6	164.1	29.7
4	Shoulder Height	129.3	131.1	133.6	135.8	139.5	143.6	147.8	151.8	154.1	156.8	158.6	29.3
5	Waist Height	93.6	95.1	97.5	99.5	102.8	106.4	109.9	113.1	115.2	117.5	119.2	25.6
6	Crotch Height	72.8	74.2	76.3	78.0	80.8	83.9	87.0	89.9	91.7	93.7	95.1	22.3
7	Kneecap Height	45.5	46.4	47.6	48.7	50.6	52.8	55.0	57.1	58.4	59.8	60.7	15.2
8	Calf Height	29.3	30.0	31.1	32.0	33.6	35.4	37.2	38.9	40.0	41.2	41.9	12.6
9	Functional Reach	71.9	73.1	74.9	76.5	79.3	82.4	85.8	89.0	90.9	93.1	94.6	22.7
		Percentiles in Inches											
1	Weight (pounds)	116.0	120.1	126.3	132.1	142.6	156.3	172.6	190.1	201.9	216.5	226.9	110.9
2	Stature	62.6	64.3	64.5	65.4	67.0	68.7	70.4	72.1	73.1	74.2	74.9	12.3
3	Cervicale Height	52.9	53.7	54.8	55.8	57.2	58.8	60.6	62.1	63.0	64.0	64.6	11.7
4	Shoulder Height	50.9	51.6	52.6	53.5	54.9	56.6	58.2	59.8	60.7	61.7	62.4	11.5
5	Waist Height	36.8	37.4	38.4	39.2	40.5	41.9	43.4	44.5	45.3	46.3	46.9	10.1
6	Crotch Height	28.6	29.2	30.0	30.7	31.8	33.0	34.3	35.4	36.1	36.9	37.4	8.8
7	Kneecap Height	17.9	18.2	18.8	19.2	19.9	20.8	21.7	22.5	23.0	23.5	23.9	6.0
8	Calf Height	11.5	11.8	12.2	12.6	13.2	13.9	14.6	15.3	15.7	16.2	16.5	5.0
9	Functional Reach	28.3	28.8	29.5	30.1	31.2	32.5	33.8	35.0	35.8	36.7	37.2	8.9
	SITTING MEASUREMENTS	Percentiles in Centimeters											
10	Vert. Arm Reach, Sitting	124.7	126.3	128.7	130.9	134.4	138.2	142.0	145.5	147.8	150.6	152.6	27.9
11	Sitting Height	82.0	83.0	84.5	85.9	88.2	90.8	93.2	95.4	96.7	98.2	99.2	17.2
12	Eye Height, Sitting	70.1	71.2	72.8	74.1	76.4	78.8	81.2	83.3	84.6	86.1	87.0	16.9
13	Mid-Shoulder Height	54.5	55.6	57.1	58.4	60.3	62.4	64.5	66.5	67.6	68.9	69.7	15.2
15	Shoulder-Elbow Length	32.6	33.1	33.8	34.5	35.6	36.8	38.1	39.3	40.0	40.8	41.3	8.7
16	Elbow-Fingertip Length	42.7	43.4	44.3	45.1	46.4	47.9	49.4	51.0	51.9	53.0	53.8	11.1
19	Knee Height, Sitting	47.7	48.5	49.7	50.7	52.2	54.0	55.9	57.6	58.7	59.9	60.6	12.9
20	Popliteal Height	38.8	39.6	40.6	41.5	42.9	44.5	46.3	47.9	48.8	49.8	50.4	11.6
21	Buttock-Knee Length	52.9	53.7	54.9	55.9	57.5	59.4	61.3	63.2	64.3	65.6	66.5	13.6
22	Buttock-Popliteal Length	44.0	44.7	45.8	46.6	48.1	49.8	51.5	53.1	54.0	55.1	55.8	11.8
		Percentiles in Inches											
10	Vert. Arm Reach, Sitting	49.1	49.7	50.7	51.5	52.9	54.4	55.9	57.3	58.2	59.3	60.1	11.0
11	Sitting Height	32.3	32.7	33.3	33.8	34.7	35.7	36.7	37.6	38.1	38.6	39.0	6.7
12	Eye Height, Sitting	27.6	28.0	28.6	29.2	30.1	31.0	32.0	32.8	33.3	33.9	34.3	6.7
13	Mid-Shoulder Height	21.5	21.9	22.5	23.0	23.7	24.6	25.4	26.2	26.6	27.1	27.4	5.9
15	Shoulder-Elbow Length	12.8	13.0	13.3	13.6	14.0	14.5	15.0	15.5	15.7	16.1	16.3	3.5
16	Elbow-Fingertip Length	16.8	17.1	17.4	17.8	18.3	18.8	19.5	20.1	20.4	20.9	21.2	4.4
19	Knee Height, Sitting	18.8	19.1	19.6	20.0	20.6	21.3	22.0	22.7	23.1	23.6	23.9	5.1
20	Popliteal Height	15.3	15.6	16.0	16.3	16.9	17.5	18.2	18.8	19.2	19.6	19.9	4.6
21	Buttock-Knee Length	20.8	21.2	21.6	22.0	22.6	23.4	24.1	24.9	25.3	25.8	26.2	5.4
22	Buttock-Popliteal Length	17.3	17.6	18.0	18.4	19.0	19.6	20.3	20.9	21.3	21.7	22.0	4.7

Figure 7-2. (cont'd)

7-2 GRILLE FACE AIR VELOCITY

Reference: AMCP 706-361, Engineering Design Handbook, *Military Vehicle Power Plant Cooling.*

The equation for calculating the grille airflow velocity from the test set-up in Fig. 7-3 is:

$$V = \frac{1096.2\, C A_o \quad \Delta P/\rho}{A_g} \text{ ,ft/min} \tag{7-2}$$

where

V	= face velocity, ft/min
A_o	= area of orifice, ft^2
A_g	= effective area of grille, ft^2
ΔP	= pressure drop across orifice, in. of water
ρ	= air density before orifice, lbm/ft^3
C	= orifice coefficient, dimensionless and unitless

The units of this equation are U.S. customary; the problem is to modify the equation for SI units. The modification is made as described in par. 4-7.2.

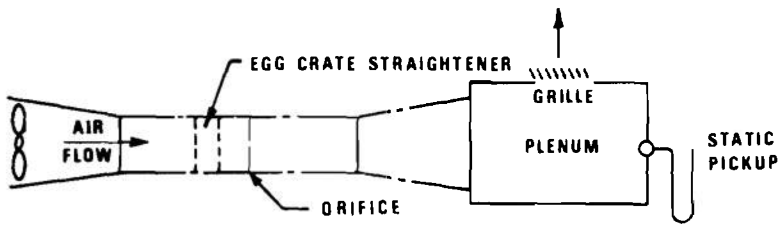


Figure 7-3. Grille Airflow Test Set-up and Instrumentation Design

The first step is to solve Eq. 7-2 for the numerical constant 1096.2. This gives:

$$1096.2 = \frac{A_g V}{C A_o \sqrt{\Delta P/\rho}} = \frac{A_g V}{C A_o} \times \left(\frac{\rho}{\Delta P}\right)^{1/2} \tag{7-3}$$

The next step is to determine the units, if any, of the constant. (Since A_g and A_o are expressed in the same units, ft^2, they "cancel" each other and can be eliminated from the problem.)

$$\{1096.2\} = \frac{(\text{ft/min}) \times (\text{lbm/ft}^3)^{1/2}}{(\text{in. of water})^{1/2}} = \frac{\text{ft} \bullet (\text{lbm})^{1/2}}{\text{min} \bullet (\text{in. of water})^{1/2} \bullet (\text{ft}^3)^{1/2}}$$

$$= \frac{(\text{lbm})^{1/2}}{\text{min} \bullet (\text{in. of water})^{1/2} \bullet \text{ft}^{1/2}} \tag{7-4}$$

Thus Eq. 7-2 can be rewritten:

$$V = \left[1096.2 \times \frac{(\text{lbm})^{1/2}}{\text{min} \bullet (\text{in. of water})^{1/2} \bullet \text{ft}^{1/2}}\right] \frac{A_g \sqrt{\Delta P/\rho}}{C A_o} \tag{7-5}$$

If the constant as expressed here is converted to SI units, Eq. 7-5 can be used with SI units.

The appropriate unit inequalities are (from Table 5-1 or 5-2):

1 in. of water (39.2°F)	= 2.490 82 $\times$ 10^2 Pa
1 lbm	= 4.535 923 7 $\times$ 10^{-1} kg
1 in.	= 2.54 $\times$ 10^{-2} m
1 ft	= 3.048 $\times$ 10^{-1} m
1 min	= 60 s

As described in par. 4-4, the unit equalities are used to form conversion factors which are used to convert the constant as follows:

$$1096.2 \times \frac{(\mathrm{lbm})^{1/2}}{\mathrm{min} \bullet (\mathrm{in.\,of\,water})^{1/2} \bullet \mathrm{ft}^{1/2}} \times \left(\frac{4.535\,923\,7 \times 10^{-1}\,\mathrm{kg}}{\mathrm{lbm}}\right)^{1/2} \times \frac{\mathrm{min}}{60\,\mathrm{s}}$$

$$\times \left(\frac{\mathrm{in.\,of\,water}}{2.490\,82 \times 10^{2}\,\mathrm{Pa}}\right)^{1/2} \times \left(\frac{\mathrm{ft}}{3.048 \times 10^{-1}\,\mathrm{m}}\right)^{1/2} = 1.412\,188\,804 \frac{(\mathrm{kg})^{1/2}}{\mathrm{s} \bullet (\mathrm{Pa} \bullet \mathrm{m})^{1/2}} \quad (7\text{-}6)$$

The number with the smallest number of significant digits in this calculation is $2.490\,82 \times 10^{2}$. Thus according to the rules of par. 4-2.3, the result should be rounded to six significant digits as is done in Eq. 7-7.

$$V = \frac{1.412\,19\,C A_g \sqrt{\Delta P/\rho}}{A_g}, \mathrm{m/s} \quad (7\text{-}7)$$

It is obvious that the constant in both the original equation, Eq. 7-2, and the SI equation, Eq. 7-7, has units. Therefore, to have converted Eq. 7-2 to SI units by merely adjusting the dimensions of ΔP and ρ would have yielded an erroneous result — units were "hidden" in the constant term.

7-3 EFFECTS OF WORKING ENVIRONMENT ON HUMAN PERFORMANCE

Reference: AMCP 706-134, Engineering Design Handbook, *Maintainability Guide for Design*, August 1967.

The heat factor is probably one of the most important environmental factors in reducing the operational efficiency of personnel. The impact of heat on human performance is a function of humidity as illustrated in Fig. 7-4. This illustrates the increasing inability of man to tolerate heat as humidity increases. The degrees of difficulty — impossible, difficult, and relatively easy — refer to the ability of a man to perform equipment maintenance without excessive errors.

A large amount of data related to human factors engineering is available in graphical form and in U.S. customary units as in Fig. 7-4. By adding a temperature coordinate in kelvins or in degrees Celsius this graph can be used in design work in SI units. Normally, environmental temperature is expressed in degrees Celsius and, in this case, a new temperature coordinate in degrees Celsius will be constructed so that the graph can be used without replotting the data. Relative humidity is independent of the system of units used. A simple procedure for constructing a new temperature scale is outlined in the following:

1. A line is constructed parallel to the temperature coordinate as illustrated in Fig. 7-4 (see line ①). This line will be the base for an additional temperature coordinate in degrees Celsius.
2. The end points, ② and ③ , for this temperature scale are identified by extending ordinates, ④ and ⑤ , through the points 90°F and 125°F on the original temperature scales until they intersect the new temperature scale.
3. Next the temperatures of the end points in degrees Celsius are obtained by converting 90°F and 125°F to Celsius temperature as described in par. 4-5:

$$(5/9)\,(90°\mathrm{F} - 32) = 32.22\ °\mathrm{C}$$
$$(5/9)\,(125°\mathrm{F} - 32) = 51.67\ °\mathrm{C}$$

These temperatures are the end-point temperatures of the new coordinate in degrees Celsius.

4. The ordinate ⑤ is now extended through the right-hand end point as shown (see ⑥).
5. The next step is to prepare a linear scale (see ⑦ in the figure) which includes values between 32°C and 53°C and of such a length that the distance between 32.22°C and 51.67°C is equal to or slightly greater than the distance between points ② and ③ , the end points, on the temperature scale being constructed. This requires graph paper or any paper with equal divisions, some luck, and some ingenuity.
6. This scale, ⑦ , is then positioned as shown in the figure such that the point 32.22°C coincides with the left-hand end point ② , and the point 51.67°C intersects the line ⑥ at point ⑧ .

7. The new temperature scale is completed by constructing lines through major divisions on the scale 7 and perpendicular to the new scale ① (see lines ⑨ in the figure).

Both coordinates of a graph can be reconstructed for using different systems of units by using the procedure outlined in the preceding paragraphs. In most cases this is considerably easier and quicker than constructing a completely new graph, or trying to construct a new scale on the existing axis.

7-4 CALCULATION OF THERMAL ENERGY ABSORBED BY VEHICLE BRAKES

Reference: DARCOM-P 706-358, Engineering Design Handbook, *Analysis and Design of Automotive Brake Systems.*

The equation for calculating the energy per unit time absorbed by the braking system in a vehicle traveling downhill and maintaining a constant speed by continuous use of the brakes is:

$$q_o = \frac{W\,V(G - R_r)\,3600}{778}, \text{Btu/h} \tag{7-8}$$

where

q_o = energy absorbed per unit time, Btu (mean)/h
W = vehicle weight, lb
V = vehicle speed, ft/s
G = road gradient, ft per ft (dimensionless and unitless)
R_r = tire rolling resistance (dimensionless and unitless)

It is assumed that G is greater than R_r. The units of this equation are U.S. customary; the problem is to modify this equation for use with SI units. The modification is made as described in par. 4-7.2.

The first step is to solve the equation for the numerical constant 3600/778. This gives:

$$\frac{3600}{778} = \frac{q_o}{W\,V(G - R_r)} \tag{7-9}$$

The next step is to determine the units, if any, of the constant*:

$$\left\{\frac{3600}{778}\right\} = \frac{\text{Btu/h}}{\text{lb} \times \text{ft/s}} \tag{7-10}$$

or

$$\left\{\frac{3600}{778}\right\} = \frac{\text{Btu} \cdot \text{s}}{\text{lb} \cdot \text{ft} \cdot \text{h}} \tag{7-11}$$

Thus, Eq. 7-8 can be rewritten:

$$q_o = \left[\frac{3600}{778}\;\frac{\text{Btu} \cdot \text{s}}{\text{lb} \cdot \text{ft} \cdot \text{h}}\right] W\,V(G - R_r) \tag{7-12}$$

If the constant as expressed here is converted to SI units, then Eq. 7-12 can be used with SI units.

The appropriate unit equalities are (from Table 5-1 or 5-2):

$$\begin{aligned} 1 \text{ Btu (mean)} &= 1.055\,87 \times 10^3 \text{ J} \\ 1 \text{ h} &= 3600 \text{ s} \\ 1 \text{ ft} &= 0.3048 \text{ m} \\ 1 \text{ lb} &= 4.448\,221\,615\,260\,5 \text{ N} \end{aligned} \tag{7-13}$$

* { } means "the units of"; see par. 4-7.

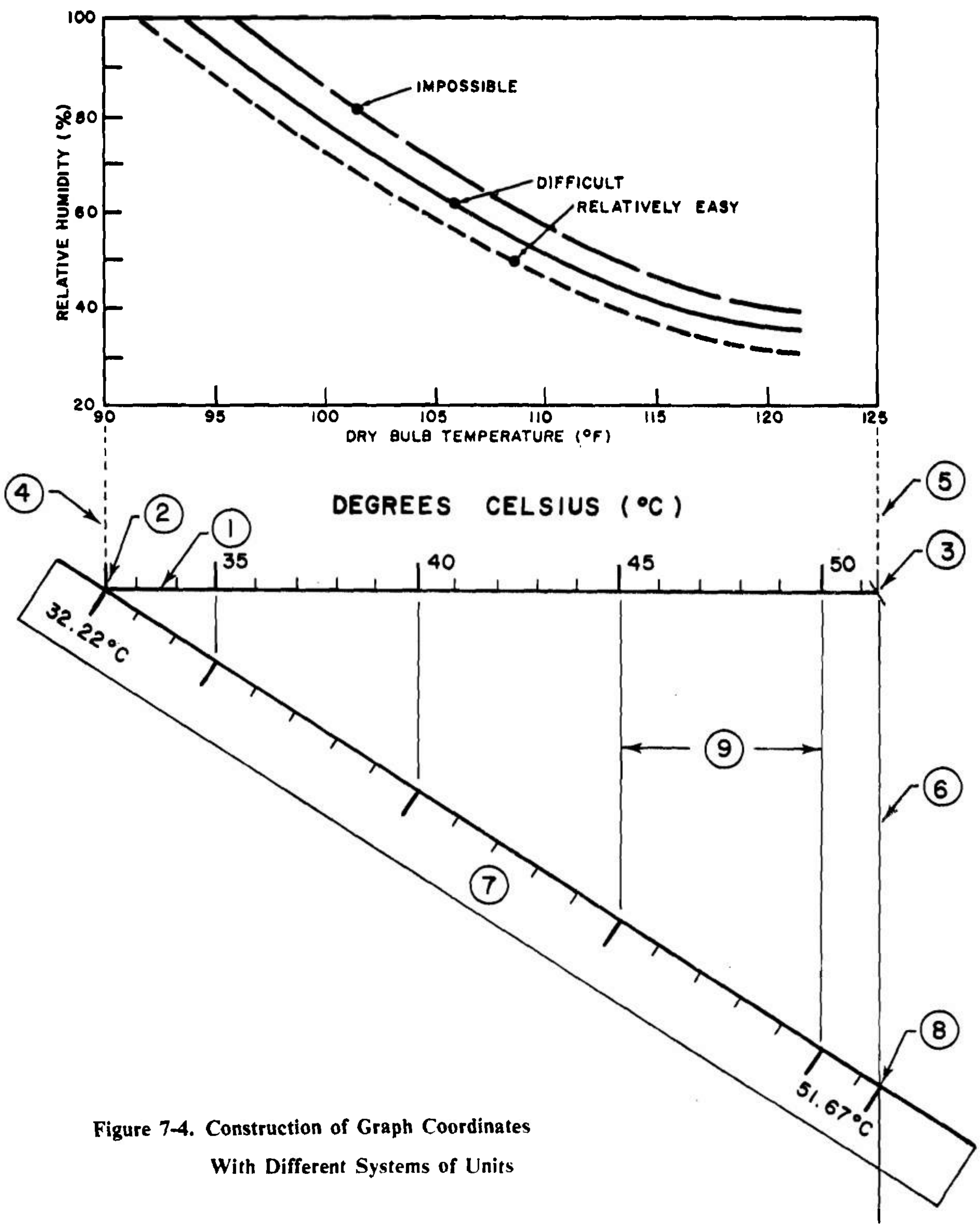


Figure 7-4. Construction of Graph Coordinates With Different Systems of Units

As described in par. 4-4, these unit equalities are used to form unit conversion factors which are used to convert the constant as follows:

$$\frac{3600}{778} \times \frac{\text{Btu} \bullet \text{s}}{\text{lb} \bullet \text{ft} \bullet \text{h}} \times \frac{1.055\,87 \times 10^3\ \text{J}}{\text{Btu}} \times \frac{1\ \text{lb}}{4.448\,221\,615\ \text{N}} \times \frac{1\ \text{h}}{3600\ \text{s}} \times \frac{1\ \text{ft}}{0.3048\ \text{m}} \tag{7-14}$$

$$= 1.000\,989 \approx 1.00, \text{ remembering the relationship J} = \text{N} \bullet \text{m} .$$

The number with the smallest number of significant digits in this calculation is 778. Thus according to the rules of par. 4-2.3, the result should be rounded to three significant digits as is done in Eq. 7-14. Thus the constant in the SI equation is approximately unity and it is dimensionless and unitless. The original equation has a nonunity constant because mixed units were used; i.e., hours and seconds, and, Btu and foot-pounds. The equation in SI units is:

$$q_o = W V (G - R_r) \text{ , J/s} \tag{7-15}$$

where

q_o = thermal energy absorbed, J/s
W = weight, N
V = speed, m/s
G, R_r are the same independently of the units used.

Actually, Eq. 7-15 can be used with either SI or U.S. customary units. When U.S. customary units are used, they cannot be mixed; all quantities must be expressed in foot-pounds for energy, pounds for weight, and feet per second for speed. The result will be in foot-pounds per second. Btu's and hours cannot be used in Eq. 7-15.

INDEX

INDEX (Continued)

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